ARIZONA DEPARTMENT OF TRANSPORTATION

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DEVELOPMENT OF FRAMEWORK FOR PAVEMENT MANAGEMENT SYSTEM FOR ARIZONA

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HIGHWAYS DIVISION · RESEARCH SECTION ·

Final Report - Phase I

DEVELOPMENT OF FRAMEWORK FOR PAVEMENT MANAGEMENT SYSTEM FOR ARIZONA

by

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Submitted to

The Arizona Department of Transportation
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16. Abstract

The investigation was designed to develop an implementable pavement management system incorporating multiple attributes of cost and performance factors.

The pavement management system compares alternate initial designs with selected maintenance procedures to determine the most appropriate combinations of design and maintenance strategies. The system also works with in-service pavements.

Unique features of the system include the use of utility theory to combine multiple attributes into a single summary value, the consideration of "tradeoffs" between attributes and the inclusion of uncertainty in the prediction models.

Computer programs have been prepared and the system is considered ready for trial implementation on selected projects within the state.

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PREFACE

Systems engineering in its broad sense is a codified procedure for attacking complex problems in a coordinated fashion to permit realistic decisions that can be justified on the basis of selected decision criteria.

Highway departments have shown an increasing interest in the development of pavement management systems starting with the publication of the National Cooperative Research Program's (NCHRP) Reports 139 and 140 which described such a system related primarily to selection of initial pavement design. An implementation project followed in which the initial development was modified to meet the needs of selected states. The results of this effort are described in NCHRP Report 160. The major pavement attribute considered in these systems was the pavement serviceability history.

In 1974, the Washington Department of Highways undertook the development of a pavement management system using different combinations of pavement attributes as compared with the NCHRP investigations, with emphasis on maintenance strategies for in-service roadways.

Arizona has initiated an extensive data acquisition program which provides the basis for a pavement management system for this state. The investigation described herein is an effort to extend the results from the NCHRP and Washington studies into an implementable system for Arizona.

As planned, the investigation involved extensive participation by the staff of the Arizona Department of Transportation in all phases of the work. The number of people who provided assistance is too large to enumerate at this time; however, particular recognition is made to Messers. Rowan Peters, George Way, John Burns, John Eisenberg, Benjamin Ong and to the Engineer of Research, Gene Morris. The cooperation of Deputy State Highway Engineer Oscar Lyons was particularly encouraging in that interest at this level indicated a commitment to the development of a pavement management system essential to its successful implementation.

1.0

BACKGROUND

A major responsibility of any transportation agency is to develop and maintain a highway network which will provide a facility meeting performance objectives at the most reasonable cost possible. A typical decision would be the selection of a specific type of pavement construction or the maintenance alternatives and sequences (strategies) which will provide an optimum application of resources. One generalized procedure for achieving such goals is the development and implementation of a pavement management system.

A pavement management system can be defined as the systematic development of information and procedures necessary in optimizing the design and maintenance of pavements. In a practical application the pavement management system will help choose the best design or maintenance strategy from among those alternatives considered appropriate for Arizona by members of the Department of Transportation staff. Maintenance procedures need not be limited to those previously used in Arizona; however, it is necessary to estimate the expected performance based on research, demonstration projects or the experience of other agencies involved in the design and construction of pavements.

Thus, a pavement management system is designed to assist the decision maker in the what, where, and when of pavement design and maintenance; what type of design and maintenance to select, where and when maintenance should be performed. It should be clear that the pavement management system cannot make a decision; only the person assigned the responsibility for the decision can do that. However, the pavement management system can provide a significant tool as an aid in making such decisions.

It is important to realize that a pavement management system (PMS) does not, of itself, develop maintenance alternatives, that is, procedures for the correction of pavement deficiencies. However, the PMS provides the framework by which alternate procedures can be compared. The system may temporarily suffer from a lack of background information for newly developed construction or maintenance concepts; for example, engineers know very little about the performance of pavements constructed with recycled materials. Hence, the pavement management system tends to lose reliability for this particular alternative. To a significant degree the ability to predict future performance depends on observations of past performance.

In order for the PMS to provide decision-making information, it is necessary to determine the appropriate dependent variable, that is, what factor or factors should be used as the major determinants for an engineering decision. The first such variable that would come to mind is cost. However, the decision need not be exclusively based on minimizing cost. It could be that for some reasonable (acceptable) increase in cost a desirable improvement in riding quality could be achieved. Hence, some tradeoff may be possible between cost and improved long-term performance.

The PMS should reflect the preferences of those who have the responsibility for the selection of design and maintenance policy with regard to both general guidelines and specific project-by-project determinations. It is not the purpose of the PMS to produce decision recommendations which would be significantly at variance with those individuals who make such decisions at the present time. The system should generally produce information which reflects the experience, preference and priorities of responsible members of the Arizona DOT staff.

In the following sections of this report an effort is made to summarize the initial phase in the development of a pavement management system for the Arizona DOT; the Appendices are provided for those interested in further explanations and discussions regarding the details of the investigation.

2.0
OBJECTIVE

The principal objective of this investigation was to develop a framework or model for a pavement management system which would provide a rationale for the decision maker in selecting (1) the optimum initial structural design and maintenance strategy for new pavements and (2) the optimum maintenance strategy for in-place (existing) pavements.

In order to achieve this objective it was necessary to undertake the following tasks:

1. Identify pavement attributes
2. Identify pavement maintenance alternatives
3. Develop models for predicting pavement attributes
4. Develop models for predicting costs
5. Develop appropriate "tradeoffs" or utility functions for the pavement attributes to be included for optimization by the pavement management system.

For purposes of this investigation an attribute is defined as some pavement characteristic which is considered to significantly influence the overall acceptability of the pavement to the user. For example, riding comfort is probably the most significant attribute that a pavement may possess; however, riding comfort is not the only attribute desired or required for a pavement.

An additional objective for the development of the PMS is to recognize uncertainties in the models with regard to the ability to predict attributes. The inclusion of uncertainty allows the decision maker to assign levels of reliability as a requirement for optimization by the pavement management system. For example, on the Interstate System a high reliability requirement of 90 or 95 percent could be used and on the Secondary System a requirement of 60 to 75 percent would not be unreasonable.

In order to develop a management system it is necessary to identify maintenance alternatives; hence, one requirement was to enumerate those procedures currently considered appropriate for Arizona. It can be expected that additional procedures will be incorporated in the future; however, in order to develop a complete working system at this time it was the Consultant's recommendation to proceed with those alternatives for which the DOT has or is accumulating the most experience.

3.0

APPROACH

In order to obtain the necessary information and to develop a data base for performance and cost, a considerable amount of interaction was necessary with the Arizona DOT staff. The overall approach used in achieving the objectives is described in the following sections of this report.

3.1 IDENTIFICATION OF PAVEMENT ATTRIBUTES

The identification of pavement attributes was accomplished in a meeting with Headquarters personnel and the Pavement Management Steering Committee on September 23 and 24, 1975. At that meeting the Consultant presented a tentative list of objective functions and pavement attributes as shown in Figure 1. The attributes were generally identified with: (1) safety, (2) riding comfort, and (3) physical distress. The specific measurements for the attributes were: (1) skid number, (2) rut depth, (3) roughness, and (4) dollar cost.

Pavement cracking did not appear in the original recommendation for the following reasons:

1. There are no reliable procedures for predicting cracking as to when or how much will occur;
2. There is no information to estimate the cost required to maintain a pavement as a function of the amount of cracking;
3. There is no information for relating cracking to pavement serviceability (riding quality); and

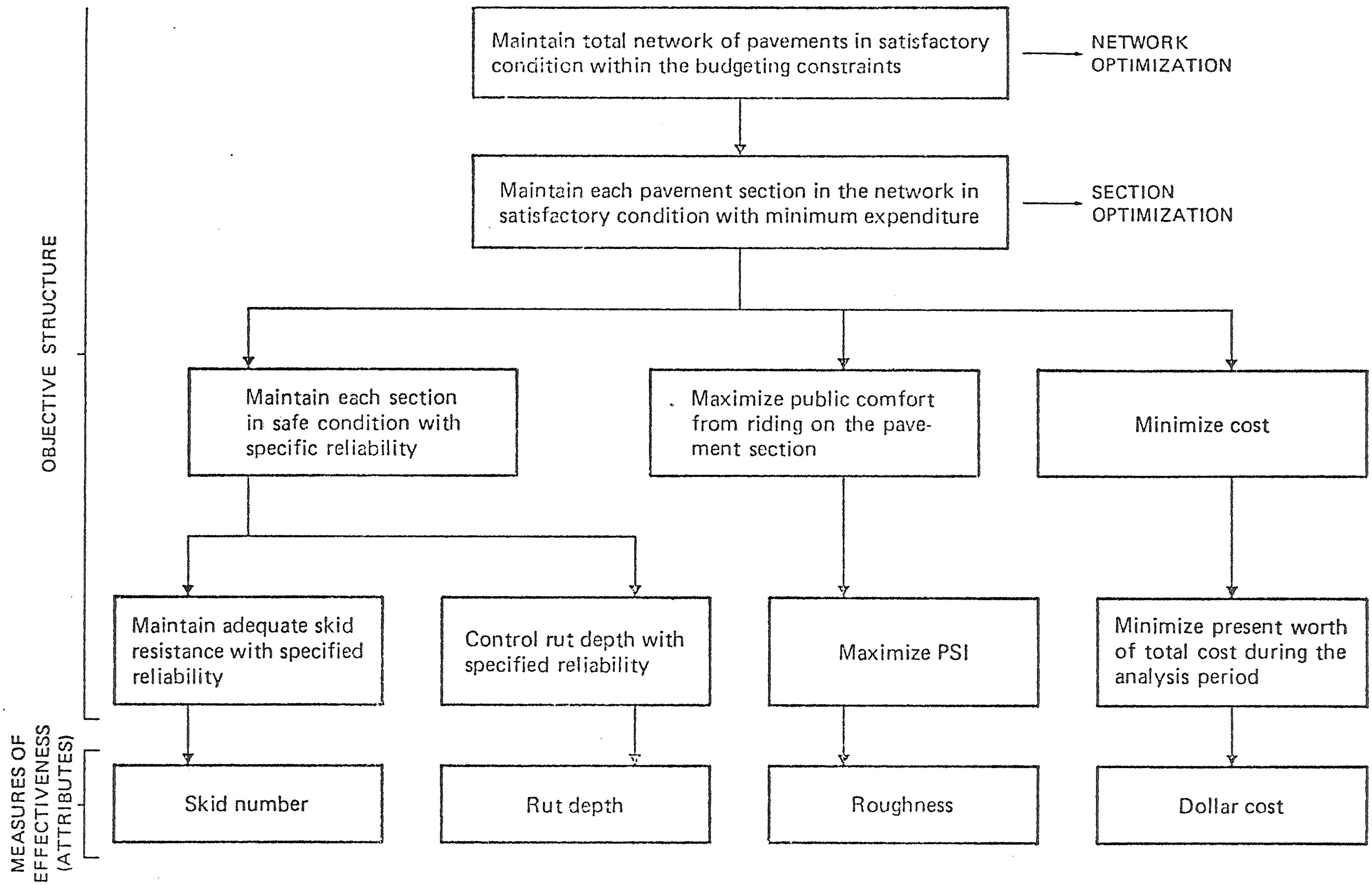

Figure 1. OBJECTIVE STRUCTURE AND MEASURES OF EFFECTIVENESS (Attributes)

4. there is no information as regards the limiting value of cracking.

It is conceded that cracking is an important pavement attribute; however, for the above reasons it was deferred from the present model until such time as one or two of the above problems can be resolved.

In lieu of predicting cracking, the Consultant proposed to substitute pavement deflection, that is, deflection to serve as a proxy for both structural strength and pavement condition. It is postulated that the average or distributed deflection, for example, 80 percentile or average plus two standard deviations, for a given pavement will reflect the amount of cracking — increasing deflection with increasing amounts and severity of cracking. This assumption is predicated on a random selection of locations for which deflection measurements are to be obtained.

Rut depth was also deleted since this type of physical distress is not presently a problem in Arizona and would not be necessary for the management system.

The Consultant recognized the need for assigning some value for excess user costs related to any inconvenience incurred by the travelling public due either to the condition of the pavement or delays related to maintenance (construction).

The ability to identify excess user costs, due to the condition of the pavement, requiring the user to slow down has not been sufficiently developed to justify its inclusion in the system. Kher (1976) reported that passenger car speed reductions do occur as the pavement becomes very rough; however, there is no evidence that commercial vehicles reduce speed. Since there is poor agreement on the value of passenger car time it was not considered; and since trucks seem not to be affected, the factor becomes moot.

It is recognized that vehicle operating costs are an important consideration to the user of a highway. The excess operating costs as a function of the condition of the pavement are not known; hence, this factor was not considered directly in the development of the System.

Though the excess user costs associated with pavement condition were not directly included in the cost attribute, it should be pointed out that the decision maker's perception of the benefit (or penalty) of better (or worse) pavement condition was captured in the PMS by considering tradeoffs between cost and roughness index, and between cost and skid number.

The final factor related to user inconvenience was the consideration of delays due to construction for major maintenance. Provision has been made for this factor in the model by including the attributed time delays associated with major maintenance.

In summary, after discussion with the Arizona DOT, the pavement attributes required for the PMS were determined to be: (1) skid number, as measured by the Mu meter; (2) longitudinal roughness as measured by the Mays meter; (3) dollar costs for routine and major maintenance; and (4) time delays associated with major maintenance.

Based on discussions with staff engineers and review of state reports,* tentative limits for skid number and roughness index were as follows:

Skid number —	43 minimum for all classes of roads
Roughness index —	40 maximum for Interstate and major primary, 50 maximum for primary, secondary and other classifications.

*Cornell (1973); Allen, Cornell, Burns, and Eisenberg (1974); Burns (1973); and Arizona Highway Department Reports Nos. 3 and 10.

3.2 MAINTENANCE ALTERNATIVES

Our understanding is that major maintenance recommendations originate in the field at the district level and are reviewed and sometimes revised by headquarters staff. Thus, the criteria for deciding when and what type of maintenance tends to be somewhat subjective at the present time. Guidelines for the selection of appropriate maintenance have been prepared by headquarters staff and are shown in Figure 2. It is pertinent to note that one of the objectives of the pavement management system is to systematize and document those decisions, but not necessarily to radically change the type of recommendation which is made in the field on the basis of experience and judgment. As a matter of fact, in the initial stages one of the tests for the system will be the reasonableness of the decision as evaluated by experienced engineers.

It is necessary to divide maintenance into two categories: (1) routine and (2) major. In our discussions it became evident that it would be necessary to differentiate between these two types of maintenance.

For purposes of the comparisons to be included in the pavement management system, the Consultant recommends the following:

1. Routine maintenance is that maintenance which would be accomplished on a systematic basis according to Department policy. This would include, as a minimum, items 101 through 109 and 119 of the PECOS maintenance management program. Routine maintenance would also include the uses of flush seals to be scheduled by the District Engineer.

2. Major maintenance would include all procedures not specifically included under routine maintenance, and which generally involve treatment of the total paved area and such modifications to the shoulder area as are required for safety and comfort. The most common type of major maintenance to be considered by the pavement management system will be an asphalt concrete overlay including seal coats on the secondary routes only.

ASPHALTIC CONCRETE REHABILITATION
(FORMAT PATTERNED AFTER NCHRP PROJECT I-10(17))

DISTRESS MODE	DISTRESS MANIFESTATION	DISTRESS MECHANISM	POTENTIAL MEASUREMENT TECHNIQUE	POSSIBLE SOLUTIONS
Fracture	Cracking	Inadequate Structure	Deflection (Dynaflect)	(1) Overlay (Mean Deflection >1.1 mils (Other) .8 mils (Interstate), All Cracking <10%) (2) Membrane & Overlay (mean Defl >1.1 mils (Other) .8 mils (Interstate), Random and Alligator Cracking >50%) (3) Membrane & ACFC (Mean Defl <1.1 mils (Other) .8 mils (Interstate), Random and Alligator Cracking >50% (4) H-S & ACFC (Mean Defl <1.1 mils (Other) .8 mils (Interstate), Block and Transverse Cracking >50%) (5) H-S & Overlay (Mean Defl >1.1 mils (Other .8 mils (Interstate), Block and Transverse Cracking >50%)
		Repeated Loading (i.e. fatigue	Cracking Index (Random & Alligator)	
		Thermal Changes (i.e. Shrinkage)	Cracking Index (Block & Transverse)	
Distoration	Permanent Deformation	Inadequate Structure	Deflection (Dynaflect) - Mays	(1) Overlay (Deflection >1.1 mils (Other) .8 mils (Interstate)
		Creep	Visual Assessment - Mays	(1) Overlay (2) H-S & Overlay (3) Reconstruction
		Densification	Rut Depth	(1) Overlay
		Consolidation	Rut Depth & Longitudinal Cracks	(1) Overlay (2) Membrane and Overlay
		Swelling	Swell Tests	(1) Membrane and Overlay (Swell >5%)
Surface Failure	Stripping & Raveling	Adhesion (i.e. Loss of Bond)	Cohesiometer – (Mr) – Visual	(1) Recycling (If Curable by Additive) (2) Reconstruct
		Abrasion by Traffic	Visual Assessment	(1) Chip Seal (ADT <1000) (2) ACFC (ADT >1000)
		Durability of Binder	Viscosity	(1) Flush (Rejuvenator) (Viscosity High) (2) Flush (Asphalt) (Viscosity Moderate)
Surface Friction		Polishing Bleeding	Skid Number (Mu-Meter)	(1) Chip Seal (No Bleeding, ADT <1000, Sn <43) (2) ACFC (Low Bleeding Sn <43) (3) H-S & ACFC (Heavy Bleeding, Sn <43) (4) Slurry Seal*

NOTE: Deflection Values are Nominal Values for "Average" Roadway with the Need for Overlay Based on Remaining Life of 5 years or Less.

NOTE: H-S Refers to Heater-Scarification. Mr Refers to Modulus of Resiliency.

*Alternate in lieu of 1 to 3 (Temporary Expedient)

Figure 2. CURRENT GUIDELINES FOR SELECTION OF MAINTENANCE TYPE

As the pavement management system is perfected and the data bank accumulates more information it should be possible to extend major maintenance to include such factors as the flush seal or improved subsurface drainage for the asphalt pavements and grinding or subsealing of Portland Cement Concrete (PCC) pavements. Also, reclamation of existing pavements can be included when information becomes available.

Major maintenance to be considered at this time is as follows:

a. For Portland cement concrete pavements —

   Asphalt concrete friction course (ACFC) with and without asphalt rubber membrane;

b. For asphalt type pavements on Interstate or major primary routes —

   -ACFC with and without rubber membrane;

   -ACFC with and without heater-remix (scarifier);

   -ACFC with increasing thicknesses of asphalt concrete overlays, up to 4 inches, with and without rubber membrane and with or without heater-remix (Note: the limiting value of 4 inches is considered tentative and based on a paper by G. Morris to the Rubber Reclaimers Association entitled, "Asphalt-Rubber Membranes: Development, Use, Potential."); and

   -ACFC with increasing thicknesses of asphalt concrete overlays greater than 4 inches, without rubber membrane or heater-remix.

c. For asphalt type pavements on secondary and other routes —

   -All of those considered under Item b; and

   -Chip seals on existing pavements.

3. A third maintenance consideration will subdivide major maintenance (or betterment) into either preventive or corrective categories. Preventive maintenance considers some type of betterment before the pavement condition falls below limiting values. Corrective maintenance assumes the pavement is at or below a limiting value indicating the need for improvement.

3.3 DEVELOPMENT OF PREDICTION MODELS

As previously discussed, a requirement of the pavement management system is to predict the values of specific attributes with time. One procedure to develop such prediction capability is by means of regression analysis using data obtained from measurements. For this investigation there was a minimum of objective data (measurements). It was therefore necessary to develop subjective data from experience. It is pertinent to note that the appropriate measurements are now being made; however, the data base up to the present time is insufficient for the development of the prediction models. Future updating based on field measurements should improve the reliability of the model and strengthen the objectivity of the models.

In order to generate the data base of information required for the prediction of road roughness, it was jointly agreed with DOT staff that the following factors should be included in the regression model:

1. Traffic — expressed in terms of equivalent 18 kip (8200 Kg) single-axle loads.
2. Deflection — as obtained with a Dynaflect and converted into equivalent Bankelman beam values for a 9 kip (4100 Kg) dual tire loading (asphalt pavements only). Deflections for pavements which are being considered for initial design (prior to construction) can be estimated by using layered system computer programs such as CHEV5L or PSAD, either of which are currently in the Arizona DOT program library. Alternatively, past experience with similar construction can be used as a first trial. For the present development, estimates of deflection were obtained from the subjective judgments of engineers currently involved in making such measurements.
3. Environment — the state was divided into three zones for this initial effort as follows: (1) 0 to 5000 feet, (2) greater than 5000 feet and (3) greater than 5000 feet with swelling clay foundation.
4. Age — the age in years since initial construction or the latest betterment (major maintenance).

5. Thickness — the thickness of the PCC slab (Portland cement concrete pavements only) or thickness of overlay (asphalt pavements only).

The prediction model for skid number included the following types of information:

- Aggregate Types — the dominant aggregates used in the state are limestone, granite and basalt; each aggregate type was coded for the regression
- Environment, Age, and Traffic — the same as used for the roughness prediction model.

Some question has been raised regarding the use of the 5000 foot elevation to identify a difference in environment which could significantly influence the annual change in road roughness. Possibly this value should be set at 3000 feet. For the development of the PMS framework it is sufficient to recognize the potential influence of elevation; future updating can more accurately define the most appropriate limits.

Traffic input for skid number could also be considered in terms of annual daily traffic (ADT); however, again, as a first iteration it is considered that equivalent 18 kip (8200 Kg) loads will reflect the total traffic volume.

As previously indicated, the limited amount of field data dictated an alternate approach for generating the type of information required for predicting roughness index and skid number for pavements. The alternative approach was to quantify the experience of engineers within the DOT in such a way as to obtain sufficient information for a first iteration of a prediction model. A general description of the type of information obtained and the procedure used for generating subjective data is given in Appendix A.

It is pertinent to discuss the use of deflection as a determinant of future roughness since a great deal of reliance is being given to the role of this particular measurement. A number of field studies have shown that deflection can effectively be used as a determinant of performance; three of the most notable would be represented by results of the AASHO Road Test (1962), studies by the Ontario (Canada) Ministry of Transportation and Communication (1965) and developments of the Asphalt Institute (1969). For over 20 years the California Transportation Laboratories have used deflection as a design parameter. Their latest procedures are described in "Structural Overlays for Pavement Rehabilitation."* With this background of results, and others, the Consultant considered deflection a reasonable proxy for pavement in-situ strength and condition (cracking).

The results of the analysis obtained from the subjective data base are illustrated in Figures 3 and 4 for the change in roughness index (CRI) and Figure 5 for change in skid number (CSN). The equations used to predict these changes are as follows:

<u>For new or in-service construction</u>

$$\ln CRI = 0.8815 \ln RGN + 0.6965 \ln DEFL + 0.1901 \ln TRAF + 0.4217 \ln AGE + 1.6638 \quad (1)$$

where

CRI = annual change in roughness index

RGN = environmental region as previously defined

DEFL = equivalent Benkelman beam deflection obtained from correlations with Dynaflect measurements

TRAF = average <u>annual</u> equivalent 18 kip (8200 Kg) single-axle loads estimated for the specific roadway

AGE = age of the pavement in years

For the example parameters shown in Figure 3 the expected change in roughness index (CRI) in the eighth year is 5.80; thus, from the eighth to ninth year the roughness index would be expected to increase by 5.80 units.

*Bushey, Baumeister, and Mathews (1975).

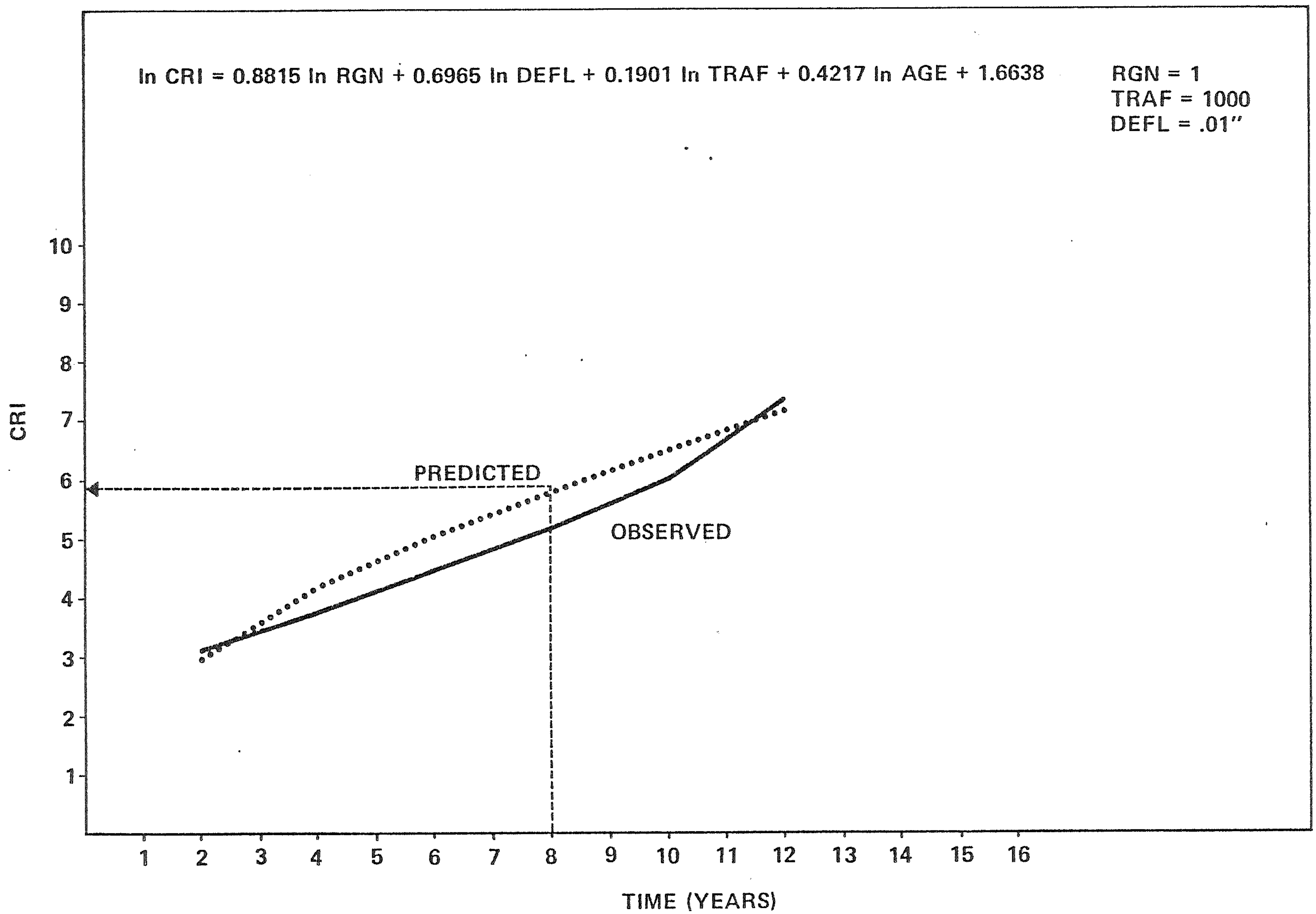

Figure 3. CHANGE IN RI FOR AC PAVEMENTS (New or in-service construction)

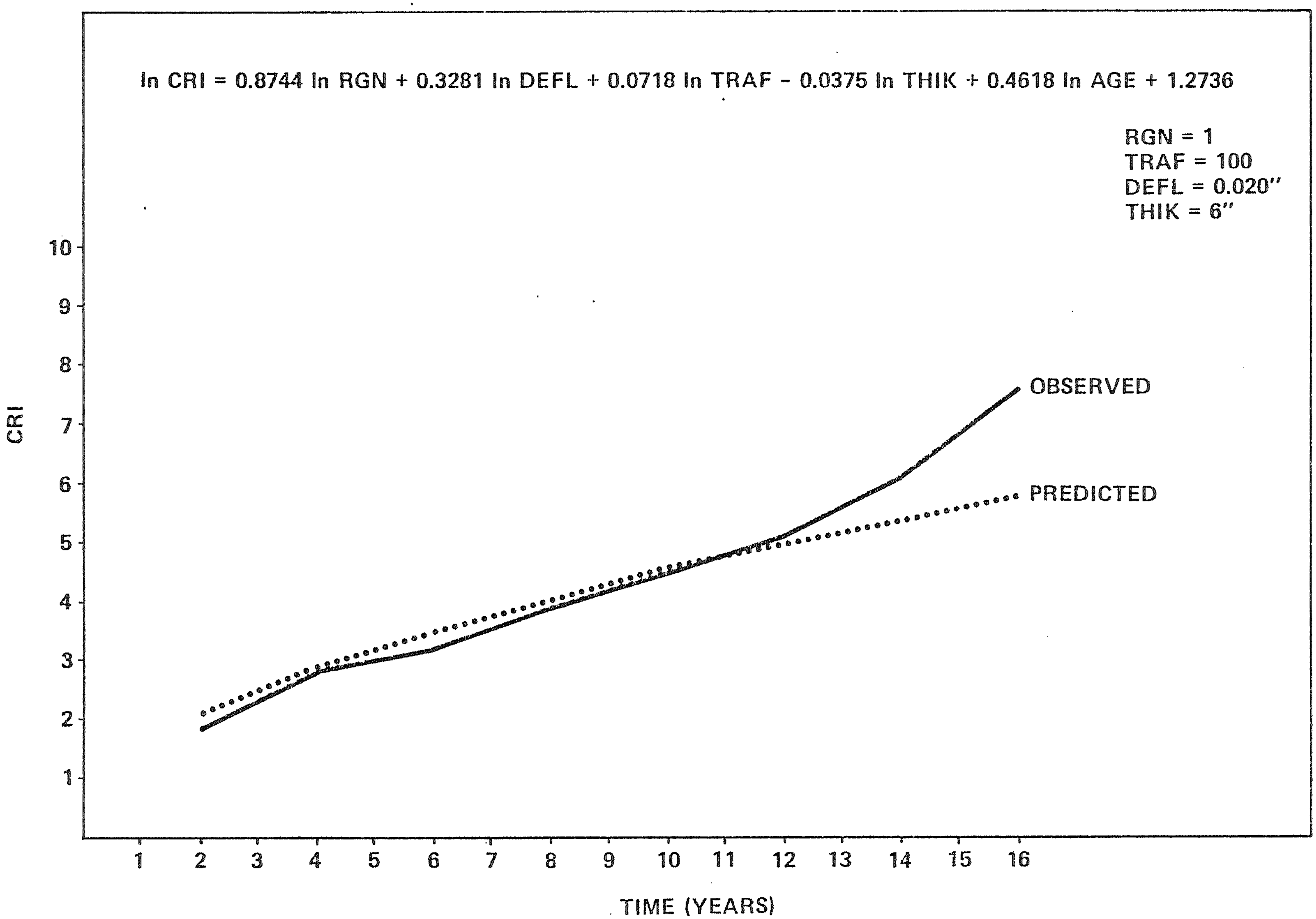

Figure 4. CHANGE IN RI FOR AC PAVEMENT (Major maintenance): 6" OVERLAY + ACFC, NO RUBBER, NO H.S.

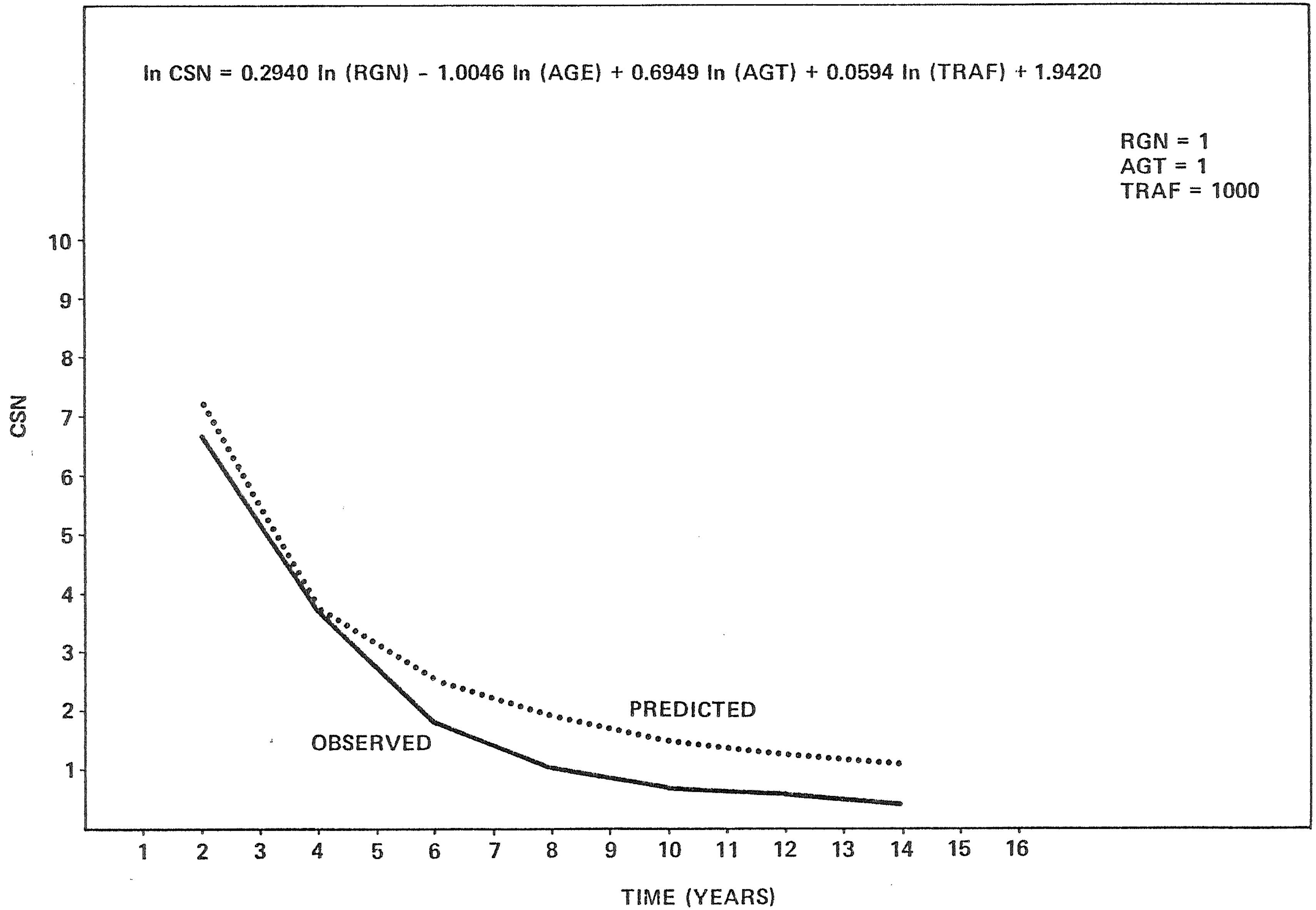

Figure 5. CHANGE IN SN FOR ACFC

For an overlay plus an asphalt concrete friction course without an asphalt-rubber inner-layer or heater-scarification

$$\ln CRI = 0.8744 \ln RGN + 0.3281 \ln DEFL + 0.0718 \ln TRAF - 0.0375 \ln THIK + 0.4618 \ln AGE + 1.2736 \quad (2)$$

where

CRI, RGN, DEFL, TRAF, and AGE are the same as used in equation (1) and

THIK = thickness of the overlay

For new construction or overlays

$$\ln CSN = 0.2940 \ln RGN - 1.0046\ AGE + 0.6949 \ln AGT + 0.0594 \ln TRAF + 1.9420 \quad (3)$$

where

CSN = annual change in skid number

RGN, AGE, and TRAF are the same as used in equation (1) and

AGT = type of aggregate; 1 for basalt, 2 for gravel, and 3 for limestone.

A complete listing of all prediction equations is given in Appendix A.

Because of the uncertainties in environment, traffic, material properties, etc., exact predictions of future pavement performance are generally not possible. The decision making process must explicitly take into account these uncertainties. To illustrate this problem, consider an example in which, for the sake of simplicity, only the roughness index was a consideration and suppose it is desired to formulate the best maintenance strategy for an in-service pavement with a maximum allowable roughness index of 40. Figure 6 can be used to illustrate the example. Assume the current measurements on the section indicate a roughness index of 25 which is considered a single value and does not include any prediction errors. The best estimate of roughness index values at 2, 4, and 6 years in the future is indicated by the

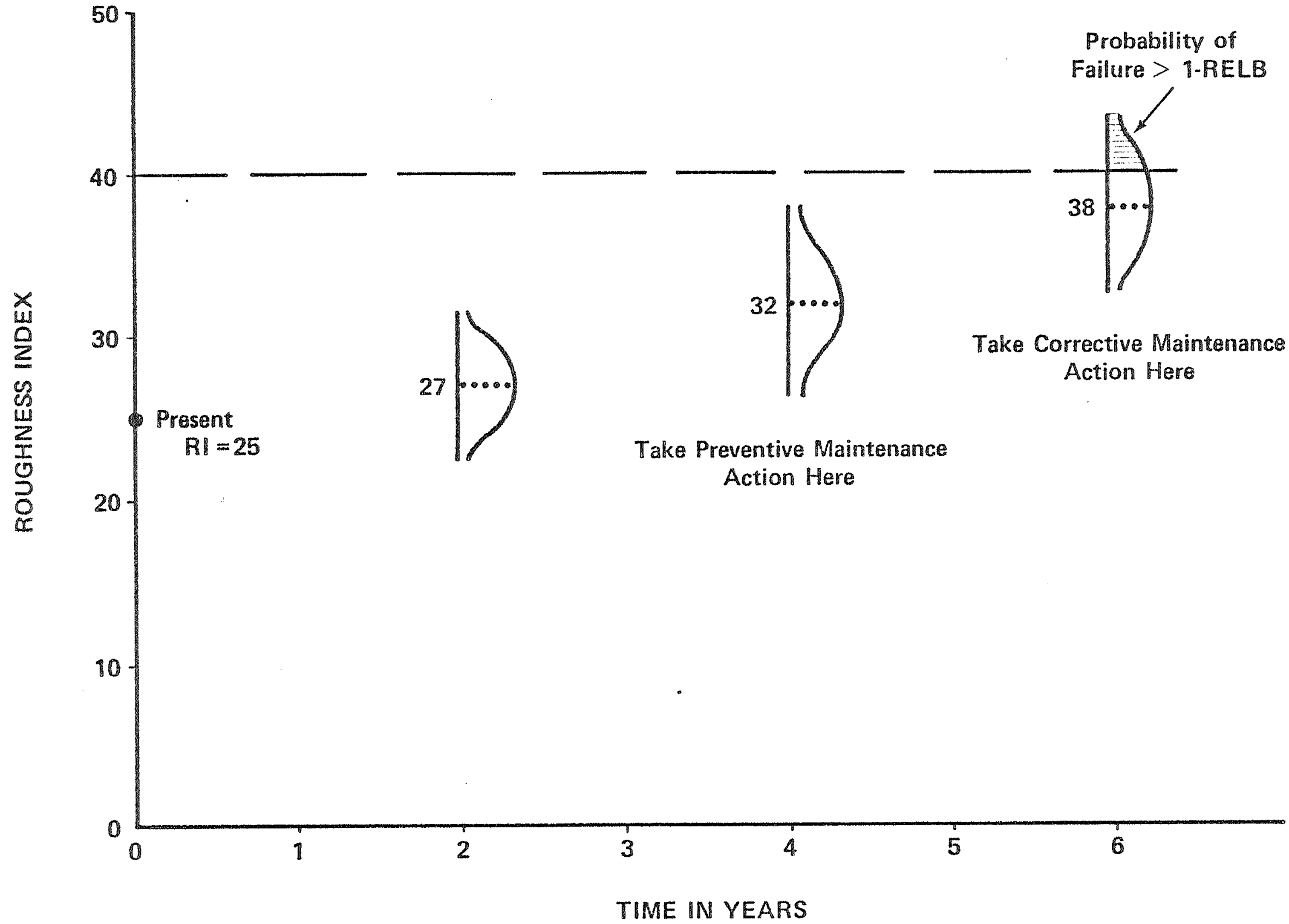

Figure 6. CONSIDERATION OF RELIABILITY IN SELECTING FEASIBLE MAINTENANCE STRATEGIES

central values of 27, 32, and 38 respectively. However, there is a chance that the value could be higher or lower than the expected value as indicated by the normal distribution curves at each time period. Thus, in 6 years there is, for example in Figure 6, a 30 percent chance that the roughness index would exceed 40. If a 70 percent reliability were specified, corrective maintenance would be required during the sixth year and preventive maintenance should be investigated at the fourth year for possible implementation in the fourth or fifth year. Thus, the level of reliability required would influence the final decision recommendation.

3.4 COST INFORMATION

Cost factors included in the pavement management system are:

1. Cost of new construction will be obtained from the SAMP 6 program developed under the National Cooperative Research Program which outputs construction costs for alternate pavement designs on a square yard basis which can be converted to a lane mile basis for input to the Arizona pavement management system.

   The SAMP 6 program provides a series of alternate designs based on the results of the AASHO Road Test. The pavement management system will project the selected optimum designs to Arizona conditions.

   The SAMP 6 program is currently operational on Arizona DOT computers with Arizona cost information.

2. Routine maintenance or those costs which are routinely scheduled in order to control the rate of deterioration and to keep the general level of serviceability above minimum levels. The amount of money required to maintain the roadway through routine maintenance will determine to a large degree when major maintenance will be required.

   The data base of information for routine maintenance could be the maintenance management system identified as PECOS. Discussion with the managers of this system indicate that additional controls and data processing will be required before the appropriate information can be obtained directly from PECOS.

As an interim procedure the Arizona DOT staff has developed an equation for estimating routine maintenance costs based on age and condition.

$$RM = -200 + 10 \times (\text{Roughness Index}) + 35 \times (\text{Age}) \qquad (4)$$

3. Costs of major maintenance are those costs related to overlays or such other betterments as are deemed appropriate to a major improvement in the condition of the pavement. Lane mile costs for various maintenance alternatives were provided by the Arizona DOT staff.

4. Salvage value was determined as a function of the remaining life at the end of the designated design or comparison period, usually 20 years although not limited to this period.

$$\text{Salvage values} = \frac{\text{Remaining life of last overlay}}{\text{Expected life of last overlay}} \times \begin{array}{l}\text{Cost of}\\ \text{last overlay}\end{array} \qquad (5)$$

Cost can be summarized in terms of their discounted present worth value or in terms of equivalent annual cost per lane mile. The latter value, which is simply an alternate way of expressing present worth, was used since the amounts are more easily perceived by the pavement manager. Thus, costs are calculated as follows:

$$\text{Present Worth Cost} = \sum_i RM(i) \times DF(i) + \sum_j (\text{Cost of major maintenance at time } j) \times DF(j) - (\text{Salvage value at end of analysis period}) \times DF(n)$$

$$\text{Equivalent Annual Cost} = (\text{Present Worth Cost}) \times (\text{Factor for Annual Cost})$$

where

$RM(i)$ = routine maintenance costs per lane mile during the i^{th} year

$DF(i)$ = discount factor for calculating present worth of money spent at i^{th} year.

3.5 DEVELOPMENT OF UTILITY FUNCTIONS

Most pavement management systems developed in the United States to date deal with a maximum of two attributes and are concerned only with actions based on limiting values of one of those attributes. Uncertainty has not been incorporated in any definitive way although the pavement management system developed for the Washington Highway Commission (1974) recognizes the existence of uncertainty. A typical system would be based on the attributes of cost and riding quality. The objective would be to determine the maintenance strategy which would keep the riding quality at or above the specified limiting value at the minimum cost. No consideration would be given to the level or trend of riding quality during the period prior to the time it reaches the limiting value or the uncertainty of predicting riding quality.

For the Arizona Pavement Management System it is necessary to simultaneously consider four attributes (multiple attributes) and to include uncertainty. In order to do this the Consultant has employed concepts developed in decision analysis theory (Raiffa, 1970) incorporating multiattribute utility functions.

Appendix B provides a detailed discussion of utility theory as applied to this investigation. Briefly, the procedure provides for the determination of a preference function or utility function which allows the history and uncertainty of a particular attribute to be summarized in a single utility value. Additionally, the procedure provides for combining the individual utilities for each attribute into a combined utility function using weighting coefficients determined by the techniques described in Appendix B.

Also, for a decision making problem involving multiple and sometimes conflicting attributes, for example, preference for better riding quality at some acceptable increase in cost, it is possible to establish how much the decision maker is willing to sacrifice in one attribute in order to achieve on some other attribute. These are termed as "trade-offs" between conflicting attributes and are also considered as part of the utility function.

The technique for obtaining utility functions was through an interview process with members of the Arizona DOT. The procedure and example questions used to obtain utility function are given in Appendix B.

Thus, the optimization for design and maintenance strategies is based on obtaining the maximum expected utility between alternate design and maintenance strategies.

3.6 DISCUSSION OF RESULTS

The pavement management system is represented by a computer program incorporating all of the concepts previously described. The computer program in this case is described by the acronym SOMSAC (Selection of Optimum Maintenance Strategies for Asphalt Concrete Pavements).

The user's manual for SOMSAC is provided in Appendix C which includes an example problem with all of the input and ouput information.

A parametric study of SOMSAC was conducted to find the sensitivity of the best maintenance strategy and its associated cost to the changes in the input parameters. A summary of this study for in-service pavements and for new designs is shown in Tables 1 and 2 respectively. The parameters changed in the case of in-service pavements were region, utility function, deflection, presence or absence of cracking, and limiting roughness index. For the new designs, region, utility function, and limiting roughness index were changed. The changes regarding region, deflection, cracking, and limiting roughness index are self-explanatory. A brief discussion of the two utility functions used in the parametric study is given below.

Table 1. SENSITIVITY OF THE BEST MAINTENANCE STRATEGY FOR IN-SERVICE PAVEMENTS

		REGION 1				REGION 3			
		Utility Function 1		Utility Function 2		Utility Function 1		Utility Function 2	
		Deflection		Deflection		Deflection		Deflection	
Limiting RI	Cracking	0.015 in.	0.03 in.	0.015 in.	0.03 in.	0.015 in.	0.03 in.	0.015 in.	0.03 in.
40	YES	11 Year Maint. Alt. 2 ACFC W-RC, WO-HS EAC = $711	12 Year Maint. Alt. 0 ACFC W-RC, WO-HS EAC = $880	13 Year Maint. Alt. 2 ACFC WO-RC, WO-HS 10 ACFC WO-RC, W-HS EAC = $678	14 Year Maint. Alt. 2 ACFC WO-RC, WO-HS 10 ACFC WO-RC, W-HS EAC = $718	15 Year Maint. Alt. 0 ACFC WO-RC, W-HS 8 ACFC W-RC, WO-HS 18 ACFC WO-RC, WO-HS EAC = $1238	16 Year Maint. Alt. 0 ACFC WO-RC, W-HS 8 ACFC WO-RC, W-HS 14 ACFC WO-RC, W-HS EAC = $1271	17 Year Maint. Alt. 0 ACFC WO-RC, W-HS 8 ACFC WO-RC, W-HS 16 ACFC WO-RC, WO-HS EAC = $1151	18 Year Maint. Alt. 0 ACFC WO-RC, W-HS 8 ACFC WO-RC, W-HS 14 ACFC WO-RC, W-HS EAC = $1271
	NO	21 Year Maint. Alt. 2 ACFC W-RC, WO-HS EAC = $711	22 Year Maint. Alt. 0 ACFC W-RC, WO-HS EAC = $880	23 Year Maint. Alt. 2 ACFC WO-RC, WO-HS 10 ACFC WO-RC, W-HS EAC = $678	24 Year Maint. Alt. 0 ACFC WO-RC, WO-HS 8 ACFC WO-RC, WO-HS 16 ACFC WO-RC, WO-HS EAC = $829	25 Year Maint. Alt. 0 ACFC WO-RC, W-HS 8 ACFC W-RC, WO-HS 18 ACFC WO-PC, WO-HS EAC = $1238	26 Year Maint. Alt. 0 ACFC WO-RC, W-HS 8 ACFC WO-RC, W-HS 14 ACFC WO-RC, W-HS EAC = $1271	27 Year Maint. Alt. 0 ACFC WO-RC, WO-HS 4 ACFC WO-RS, W-HS 14 ACFC WO-RC, W-HS EAC = $1094	28 Year Maint. Alt. 0 ACFC WO-RC, W-HS 8 ACFC WO-RC, W-HS 14 ACFC WO-RC, W-HS EAC = $1271
50	YES	31 Year Maint. Alt. 4 ACFC WO-RC, W-HS EAC = $626	32 Year Maint. Alt. 2 ACFC WO-RC, W-HS EAC = $737	33 Year Maint. Alt. 4 ACFC WO-RC, W-HS EAC = $626	34 Year Maint. Alt. 2 ACFC WO-RC, WO-HS 10 ACFC WO-RC, W-HS EAC = $670	35 Year Maint. Alt. 0 ACFC WO-RC, W-HS 10 ACFC WO-RC, W-HS EAC = $968	36 Year Maint. Alt. 0 ACFC WO-RC, W-HS 8 ACFC WO-RC, WO-HS 12 ACFC WO-RC, W-HS EAC = $1178	37 Year Maint. Alt. 0 ACFC WO-RC, W-HS 12 ACFC WO-RC, W-HS EAC = $910	38 Year Maint. Alt. 0 ACFC WO-RC, W-HS 10 ACFC W-RC, WO-HS EAC = $1040
	NO	41 Year Maint. Alt. 4 ACFC WO-RC, W-HS EAC = $626	42 Year Maint. Alt. 2 ACFC WO-RC, W-HS EAC = $737	43 Year Maint. Alt. 4 ACFC WO-RC, W-HS EAC = $626	44 Year Maint. Alt. 2 ACFC WO-RC, WO-HS 12 ACFC WO-RC, W-HS EAC = $670	45 Year Maint. Alt. 0 ACFC WO-RC, W-HS 10 ACFC WO-RC, W-HS EAC = $968	46 Year Maint Alt. 0 ACFC WO-RC, W-HS 8 ACFC WO-RC, WO-HS 12 ACIC WO-RC, W-HS EAC = $1178	47 Year Maint. Alt. 0 ACFC WO-RC, W-HS 12 ACFC WO-RC, W-HS EAC = $910	48 Year Maint. Alt. 0 ACFC WO-RC, W-HS 10 ACFC W-RC, WO-HS EAC = $1040

Table 2. SENSITIVITY OF THE BEST INITIAL DESIGN AND MAINTENANCE STRATEGY FOR NEW CONSTRUCTION

	Region 1		Region 3	
Limiting RI	Utility Function 1	Utility Function 2	Utility Function 1	Utility Function 2
40	11 Year / Maint. Alt. 0 Initial design - full depth 8 ACFC WO-RC, W-HS EAC = $4383	12 Year / Maint. Alt. 0 Initial design - full depth 6 ACFC WO-RC, WO-HS 14 ACFC WO-RC, WO-HS EAC = $4494	13 Year / Maint. Alt. 0 Initial design - full depth 4 ACFC W-RC, WO-HS 14 ACFC WO-RC, W-HS EAC = $4936	14 Year / Maint. Alt. 0 Initial design - full depth 4 ACFC WO-RC, W-HS 14 ACFC WO-RC, W-HS EAC = $4787
50	21 Year / Maint. Alt. 0 Initial design - full depth 8 ACFC WO-RC, W-HS EAC = $4330	22 Year / Maint. Alt. 0 Initial design - full depth 8 ACFC WO-RC, W-HS EAC = $4330	23 Year / Maint. Alt. 0 Initial design - full depth 4 ACFC WO-RC, W-HS 12 ACFC WO-RC, W-HS EAC = $4800	24 Year / Maint. Alt. 0 Initial design - full depth 4 ACFC WO-RC, W-HS 12 ACFC WO-RC, W-HS EAC = $4800

From the interviews with the district engineers and headquarters personnel, two significantly different sets of preferences were obtained. One preference set represented by utility function 1 indicated that the order of decreasing relative importance of the four attributes included in the system was: skid number, roughness index (or present serviceability index PSI), cost, and traffic delay. The district engineer with this preference structure would be willing to pay $9700 per year per lane-mile in order to improve the skid number from 25 to 45 and the same amount of money to improve the PSI from 2 to 3.8.

The second preference set represented by utility function 2 indicated that the order of decreasing relative importance of the attributes was: cost, skid number, roughness index, and traffic delay. In this case the district engineer would be willing to pay $9500 per year per lane-mile only if the skid number improved from 25 to 100 and he would pay up to $3000 per year per lane-mile to improve the PSI from 2 to 4.

The mathematical equations for these two utility functions are given in Appendix B. It is clear that the two functions represent significantly different views. The question whether these functions should be modified and which function should be used under what conditions must be resolved at the management level during implementation phase. The objective of the parametric study was to find how sensitive the best maintenance strategy would be to the choice of the utility function.

The notation used in Tables 1 and 2 is the following. Each box in the table represents a particular combination of the input parameters. A number in the left hand top corner in each box identifies the row and column of the box; for example, the box "ij" is in the "i^{th}" row and in the "j^{th}" column. In each box the best maintenance strategy is described and the equivalent annual cost (EAC) in dollars per lane-mile is indicated. A maintenance strategy consists of up to 3 maintenance alternatives adopted at different years from the start of the analysis. The time and type of each maintenance alternative are written in describing the best maintenance strategy. The maintenance alternative ACFC can be applied with or without rubber coat (RC) and with or without heat scarifier (HS); for example, the description "ACFC W-RC, WO-HS" indicates ACFC with rubber coat, but without heat scarifier. With regard to cracking, if cracking is observed at the present time the program would eliminate any maintenance alternative which did not have some provision for correcting the cracking condition. For this analysis, ACFC without rubber coat and without heat scarifier would not be scheduled at time zero if signficant cracking was observed.

The input parameters other than region, utility function, deflection, cracking, and limiting roughness index were fixed for the examples of the parametric study. A part of the computer output describing all the input data is shown in Figure 7.

The discussion of the results of the parametric study is divided into two parts, the first regarding in-service pavements (Table 1) and the second regarding new construction (Table 2). The following comments are pertinent with respect to the results shown in Table 1:

1. Region has a significant influence on the best maintenance strategy. Generally speaking, pavement condition deteriorates faster in Region 3 (elevation greater than 5000 ft and swelling clay) than in Region 1 (elevation less than 5000 ft). This necessitates more frequent major maintenance activities in Region 3 resulting in higher costs. As an example, compare results in boxes 21 and 25. Both have the same limiting roughness index (RI), cracking condition, deflection, and the same utility function. However, for box 21 associated with Region 1 the best maintenance strategy consists of only one action, namely ACFC with rubber coat and with heat scarifier at year 2 since the start of the analysis; the equivalent annual cost of this strategy is $711 per lane-mile. On the other hand, for box 25 associated with Region 3 the best maintenance strategy consists of 3 actions: ACFC without rubber coat, with

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PROBLEM NO. 1 - STATE OF ARIZONA - DEPARTMENT OF TRANSPORTATION - EXAMPLE NO. 1                    PAGE   1

CONTROL PARAMETERS

          NUMBER OF PERIODS IN THE ANALYSIS -----------------------------------        10
          NUMBER OF FEASIBLE INITIAL DESIGNS ----------------------------------         0
          NUMBER OF MAINTENANCE ALTERNATIVES ----------------------------------        10
          OPTION OF PRINTING INPUT DATA ONLY ----------------------------------         1
                    (0= PRINT INPUT DATA ONLY)
                    (1= EXECUTE THE PROGRAM)
          LIMITING VALUE OF RI ------------------------------------------------      40.0
          LIMITING VALUE OF SN ------------------------------------------------      43.0
          RELIABILITY FACTOR FOR NOT EXCEEDING THE LIMITING RI VALUE -----------      .842
          RELIABILITY FACTOR FOR NOT EXCEEDING THE LIMITING SN VALUE -----------     1.282
          INDICATOR FOR NEW DESIGN --------------------------------------------         1
                    (0= NEW DESIGN OF PAVEMENT)
                    (1= IN-SERVICE PAVEMENT)
          NUMBER OF ALTERNATIVES TO BE ELIMINATED -----------------------------         0

DESCRIPTION OF MAINTENANCE ALTERNATIVES

          ALTERNATIVE NO. 1 : ROUTINE MAINTENANCE
          ALTERNATIVE NO. 2 : ACFC WITHOUT RUBBER COAT, WITHOUT HEAT SCARIFIER
          ALTERNATIVE NO. 3 : ACFC WITHOUT RUBBER COAT, WITH HEAT SCARIFIER
          ALTERNATIVE NO. 4 : ACFC WITH RUBBER COAT, WITHOUT HEAT SCARIFIER
          ALTERNATIVE NO. 5 : 1 IN OVLAY + ACFC WITHOUT RUBBER COAT,WITHOUT HEAT SCARIFIER
          ALTERNATIVE NO. 6 : 1 IN OVLAY + ACFC WITHOUT RUBBER COAT, WITH HEAT SCARIFIER
          ALTERNATIVE NO. 7 : 1 IN OVLAY + ACFC WITH RUBBER COAT, WITHOUT HEAT SCARIFIER
          ALTERNATIVE NO. 8 : 3 IN OVLAY + ACFC WITHOUT RUBBER COAT,WITHOUT HEAT SCARIFIER
          ALTERNATIVE NO. 9 : 3 IN OVLAY + ACFC WITHOUT RUBBER COAT, WITH HEAT SCARIFIER
          ALTERNATIVE NO.10 : 3 IN OVLAY + ACFC WITH RUBBER COAT, WITHOUT HEAT SCARIFIER
```

Figure 7. INPUT DATA

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PROBLEM NO. 1 - STATE OF ARIZONA - DEPARTMENT OF TRANSPORTATION - EXAMPLE NO. 1                    PAGE  2

INFORMATION PERTINENT TO GIVEN PAVEMENT SECTION
          INDICATOR FOR PRESENCE OR ABSENCE OF ACFC ---------------------------     1
                        (0= WITH ACFC)
                        (1= WITHOUT ACFC)
          INDICATOR FOR CRACKING ----------------------------------------------     0
                        (0= NO CRACKING)
                        (1= CRACKING)
          INDICATOR FOR USING CHIP SEAL ---------------------------------------     0
                        (0= CHIP SEAL NOT TO BE USED)
                        (1= CHIP SEAL TO BE USED)
          AGGREGATE TYPE IN PRESENT CONDITION ---------------------------------   1.0
                        (1= BASALT OR CINDERS)
                        (2= GRAVEL)
                        (3= LIMESTONE)
          AGGREGATE TYPE TO BE USED IN FUTURE ACFC ----------------------------   1.0
                        (CODE SAME AS PRESENT--ABOVE)
          PAVEMENT AGE IN YEARS AT PRESENT TIME -------------------------------   8.0
          ENVIRONMENTAL REGION OF GIVEN PAVEMENT SECTION ----------------------   1.0
                        (1= LOW ALTITUDE, LOW RAINFALL)
                        (2= HIGH ALTITUDE, HIGH RAINFALL, NO SWELLING CLAY)
                        (3= HIGH ALTITUDE, HIGH RAINFALL, SWELLING CLAY)
          PRESENT DEFLECTION (IN INCHES) OF THE PAVEMENT SECTION --------------   .0150
          PRESENT RI(ROUGHNESS INDEX) OF THE PAVEMENT SECTION -----------------  27.0
          PRESENT SN(SKID NO.) OF THE PAVEMENT SECTION ------------------------  55.0

OVERLAY THICKNESS

          MAINT. ALT.   THICKNESS(INCHES)
                2             .750
                3             .750
                4             .750
                5            1.000
                6            1.000
                7            1.000
                8            3.000
                9            3.000
               10            3.000
```

Figure 7. (Cont.)

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PROBLEM NO.  1 - STATE OF ARIZONA - DEPARTMENT OF TRANSPORTATION - EXAMPLE NO. 1                     PAGE   3

PREDICTION MODELS

   1) CHANGE IN RI FOR NEW OR IN-SERVICE PAVEMENTS-
      LN(CRI) = C11 + C12 * LN(TRAFFIC) + C13 * LN(REGION) + C14 * LN(DEFLECTION) + C15 * LN(AGE)
      REGRESSION COEFFICIENTS  C11=  1.6600 C12=   .1900 C13=   .8820 C14=   .6960 C15=   .4220
      STANDARD ERROR=   .2120

   2) CHANGE IN RI FOLLOWING AN OVERLAY-
      LN(CRI) = CRH + C21 + C22 * LN(TRAFFIC) + C23 * LN(REGION) + C24 * LN(DEFLECTION) + C25 * LN(THICKNESS) + C26 * LN(AGE)
      REGRESSION COEFFICIENTS(EXCLUDING CRH)  C21=  1.2740 C22=   .0718 C23=   .8744 C24=   .3281 C25=   .0375 C26=   .4618
      STANDARD ERROR=   .2206
      CRH ARE CORRECTION FACTORS INDICATING EFFECT OF RUBBER COAT OR HEAT SCARIFIER ON PAVEMENT PERFORMANCE
      CORRECTION FACTORS (CRH) FOR GIVEN OVERLAYS
      MAINT. ALT.        CRH
             2          1.00
             3           .40
             4           .25
             5          1.00
             6           .50
             7           .33
             8          1.00
             9           .50
            10           .33

   3) CHANGE IN SN FOR NEW OR IN-SERVICE PAVEMENT-
      LN(CSN) = B11 + B12 * LN(TRAFFIC) + B13 * LN(REGION) + B14 * LN(AGG. TYPE) + B15 * LN(AGE)
      REGRESSION COEFFICIENTS  B11=  1.9720 B12=   .1007 B13=   .1147 B14=   .9393 B15= -1.4590
      STANDARD ERROR=   .2198

   4) CHANGE IN SN FOLLOWING ACFC-
      LN(CSN) = B21 + B22 * LN(TRAFFIC) + B23 * LN(REGION) + B24 * LN(AGG. TYPE) + B25 * LN(AGE)
      REGRESSION COEFFICIENTS  B21=  1.9420 B22=   .0594 B23=   .0294 B24=   .0649 B25= -1.0050
      STANDARD ERROR=   .3040

   5) RI IMMEDIATELY AFTER AN OVERLAY-
      LN(RIA) = XC0 + XC1 * LN(RIB) + XC2 * LN(T)
      REGRESSION COEFFICIENTS  XC0=  1.6280 XC1=   .3090 XC2=  -.2370
      STANDARD ERROR=   .0990
```

Figure 7. (Cont.)

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PREDICTION MODELS - CONTINUED

  6) SN IMMEDIATELY AFTER ACFC-
       AVERAGE SN IMMEDIATELY AFTER ACFC= 80.0
       STANDARD DEVIATION OF SN IMMEDIATELY AFTER ACFC= 3.333

  7) REDUCTION IN DEFLECTION FOLLOWING MAJOR MAINTENANCE-
       MAINT. ALT.    PERCENTAGE REDUCTION IN DEFLECTION
             2               0
             3               0
             4               0
             5            10.0
             6            10.0
             7            10.0
             8            20.0
             9            20.0
            10            20.0

  8) TRAFFIC DELAY DURING MAJOR MAINTENANCE OPERATIONS-
       MAINT. ALT.    AVERAGE TRAFFIC DELAY IN MINUTES
             2             7.0
             3             7.0
             4             7.0
             5             7.0
             6             7.0
             7             7.0
             8             7.0
             9             7.0
            10             7.0

       COEFFICIENT OF VARIATION OF TRAFFIC DELAY=   .1000
```

Figure 7. (Cont.)

ROUTINE MAINTENANCE COSTS-

COSTS FOR ROUTINE MAINTENANCE ARE DERIVED FROM THE FOLLOWING FUNCTION-

RMCOST = -200.0 + 10.0 * RI + 35.0 * AGE

MAJOR MAINTENANCE COST

MAINT. ALT.	MAINT. COST
2	5632.00
3	8448.00
4	11733.00
5	12766.00
6	15582.00
7	18867.00
8	27034.00
9	29850.00
10	33135.00

COEFFICIENT OF VARIATION OF COST= .1000

EFFECTIVE INTEREST RATE= 0

TRAFFIC INFORMATION

AVERAGE ANNUAL TRAFFIC DURING FIRST YEAR OF ANALYSIS= 182500.00

ANNUAL TRAFFIC GROWTH RATE(IN PERCENT)= 5.00

Figure 7. (Cont.)

heat scarifier at year 0; ACFC with rubber coat, without heat scarifier at year 8; and ACFC without rubber coat, without heat scarifier at year 18. The cost of this strategy is $1238 per lane-mile, an increase of 74% over the cost of the first strategy.

2. The deflection of a pavement has a significant effect on its performance and hence on the selection of the best maintenance strategy. A higher deflection implies a weaker pavement and a higher rate of deterioration. This would necessitate more expensive maintenance and/or more frequent maintenance. Compare boxes 23 and 24 for illustrating this point. Both boxes have the same inputs except for deflection. The best strategy for box 23 with a deflection of 0.015 in. consists of two actions: ACFC without rubber coat, without heat scarifier at year 2 and ACFC without rubber coat, with heat scarifier at year 10. The cost of this strategy is $678 per lane-mile. On the other hand, the best strategy for box 24 with a deflection of 0.03 in. consists of three actions: ACFC without rubber coat, without heat scarifier at year 0; ACFC without rubber coat, without heat scarifier at year 8; and ACFC without rubber coat and without heat scarifier at year 16. The cost of this strategy is $829 per lane-mile which is 22% higher than that of the previous strategy.

3. The choice of the utility function seems to have some influence on the best maintenance strategy. As discussed earlier, utility function 1 implies relatively higher weights on skid number and roughness index than on cost. With the assumption of this utility function one would be willing to pay relatively large amounts of money to improve skid number or roughness index from the least desirable value to some acceptable but probably not most desirable value. Utility function 2 on the other hand assigns relatively higher weight to cost than to skid number or roughness index; this utility function would require improving pavement condition from least desirable to most desirable for relatively smaller amounts of money. To illustrate the effect of choice of the utility function on the best maintenance strategy, consider boxes 21 and 23 which have the same inputs except for the utility function. For box 21 with utility function 1 the best maintenance strategy is ACFC with rubber coat but without heat scarifier and the cost of this strategy is $711 per lane-mile. With

utility function 2, one would prefer a strategy with significant reduction in cost even though this would make pavement condition somewhat worse. Because of this consideration the best maintenance strategy for box 23 with utility function 2 indicates ACFC without rubber coat and without heat scarifier at year 2 and ACFC without rubber coat, with heat scarifier at year 10; the cost of this strategy is $678 per lane-mile which is 5% lower than the previous one.

4. The limiting value of roughness index has a significant effect on the selection of the best maintenance strategy. This effect is due to the fact that if somewhat higher values of roughness index are permissible, several strategies with somewhat lower costs would become feasible, which in the case of higher maintenance standards would not have been generated by the program. To illustrate this point, consider boxes 11 and 31 which have the same inputs except for the limiting roughness index. The best maintenance strategy in box 11 requires more expensive maintenance, namely ACFC with rubber coat at year 2. On the other hand the best maintenance strategy in box 31 with higher limiting roughness index allows less expensive maintenance, namely ACFC without rubber coat but with heat scarifier at a later time (year 4). The cost reduction because of allowing higher roughness on the road is about 12%. The cost reduction is even more prominent in Region 3. For example, there is a 22% cost reduction from the best maintenance strategy in box 15 to that in box 35.

5. Whether or not cracking is present does not seem to have any significant effect on the selection of the best maintenance strategy. The reason is that irrespective of presence or absence of cracking, an ACFC with either rubber coat or heat scarifier appears to be favored at year 0 over an ACFC without either of these features. Since a rubber coat or a heat scarifier would have some corrective action with regard to cracking, a maintenance action with either of these features would be permissible even in case of cracking.

6. An observation of some significance from Table 1 is that if a higher maintenance standard is desired (limiting RI = 40) and if a higher weight is put on roughness index than on cost (utility function 1), a rubber coat is favored over a heat scarifier, while the opposite is true under other conditions. For example, an

ACFC with rubber coat is selected in boxes 11, 12, 21, and 22; an ACFC with heat scarifier is selected in boxes 31, 32, 41, and 42.

The following observations can be made from the results of the parametric study shown in Table 2:

1. The full depth initial design is consistently selected as a part of the best strategy. The comparison between the full depth design and the conventional design as used in the illustrative example shows that the full depth design is weaker (deflection of 0.024 in. as against 0.015 in. for the conventional design), but cheaper (cost of $78,220 as against $93,166 for the conventional design). Thus, even though the conventional design performs better, the full depth design with one or two relatively inexpensive ACFC's can provide similar performance with less cost.

2. In Region 3 where the rate of pavement deterioration is much higher, an early major maintenance is required following the full depth construction. The best early major maintenance would be an ACFC with a rubber membrane (see box 13) if a high standard is to be maintained (limiting RI = 40) and if the relative weight on pavement condition is higher than that on cost (utility function 1). Under other conditions, an ACFC with heat scarifier is favored.

4.0 IMPLEMENTATION

The practical application of the pavement management system is the development of a systematic procedure for arriving at design and maintenance procedures which will meet specific objectives of the Arizona Department of Transportation management level personnel.

The findings of this investigation indicate the applicability of certain principals of decision theory which have not as yet been used in management systems and which provide for the inclusion of multiple attributes used to optimize the decision recommendations.

The computer programs developed under the investigation provide a framework for incorporating current data acquisition procedures being implemented by the state and can provide guidelines as to when and where measurements should be made.

The benefits to be achieved by implementing the system should be reflected in the optimum use of available funds for the design and maintenance of individual projects and will provide the basis for a network system designed to allocate funds according to the greatest need.

Appendix D provides a recommended program for implementation to field applications and includes a description of a series of tasks necessary for the second stage investigation.

5.0 CONCLUSIONS AND RECOMMENDATIONS

Based on the progress made in this phase of the investigation it is concluded that a pavement management system can be developed for the Arizona Department of Transportation which will incorporate the desired attributes and operating preferences of the decision makers within the organization.

It is too soon to indicate what problems might occur in the implementation phase; however, it is considered that some adjustments may be required in the prediction models and in the evaluation of the impact of user inconvenience to the decision recommendations; that is, how to evaluate the interference to traffic flow due to maintenance operations.

The pavement management system, as proposed, deals with project-by-project decisions; that is, assuming funds are available, what is the optimum sequence of decisions appropriate to the design and maintenance of a pavement? The project does not deal with network optimization which would address the problem of allocation of limited funds to those projects requiring some type of major maintenance or betterment.

It is recommended that a second and third phase program be initiated. The second phase would be to test the implementability of the system described under this investigation. Only a limited amount of progress and evaluation can be achieved without field application. The third phase is the development of a framework for network optimization. If at all possible these programs should overlap somewhat in order to assure compatability of each system.

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APPENDIX A

DEVELOPMENT OF PREDICTION MODELS FOR PAVEMENT CONDITION

INTRODUCTION

In order to evaluate alternative maintenance strategies it is necessary to predict the effect of each strategy on pavement condition measured in terms of skid number and roughness index. Typically, prediction models are developed by assuming some analytical model and estimating the parameters of such a model from observed field data. Alternative models are attempted and one giving the best fit to the data is generally adopted. Such an approach could not be utilized for this project because very little "objective" data in terms of field observations was available.

The difficulty with the current data bank is the relatively limited period over which information has been collected and not the type of information being collected. It can be expected that, with time, the data bank will provide all of the information needed by the pavement management system.

As an alternative to the present situation, it was decided to develop "subjective" data from the experience and judgment of the pavement engineers from Arizona DOT. Use of subjective information in statistical analysis is quite valid. This is generally termed as the Bayesian statistical approach. Because of the time constraints, it was necessary to use a procedure which would be easily understood by the engineers and could be implemented in a relatively short amount of time. Because of these reasons, it was decided to assess subjective information in the form of pavement performance curves since engineers would be most familiar with how pavements would perform under different conditions. From the performance curves subjective data points can be generated by using some simulation procedure. The details regarding assessment of subjective information in the form of performance curves, generation of subjective data through simulation, and use of subjective data in multiple regression analyses are given in the following sections.

ASSESSMENT OF SUBJECTIVE INFORMATION

The procedure used for assessing subjective information regarding skid number and roughness index is described below.

As a first step, the factors which would affect the changes in skid number and roughness index of a pavement were determined in consultation with the Arizona DOT staff. These factors for new construction and major maintenance for asphalt concrete (AC) pavements are shown below.

Dependent Variable	Independent Variables
Change in RI following new construction	Traffic, environmental region, deflection, age
Change in RI following major maintenance	Traffic, environmental region, deflection, overlay thickness, age
RI immediately after major maintenance	RI prior to major maintenance, overlay thickness
Change in SN following new construction or major maintenance	Traffic, environmental region, aggregate type, age
SN immediately after ACFC	Aggregate type

In the above list, region was taken to represent environmental variables (rainfall, climate, swelling of clay, etc.) and deflection was assumed as a proxy variable for pavement strength. Three regions were selected:

Region 1, low altitude ($\leq$ 5000 ft); Region 2, high altitude (> 5000 ft), no swelling clay; and Region 3, high altitude (> 5000 ft), swelling clay.

Subjective information was assessed in the form of performance curves for different combinations of the independent variables for the following maintenance alternatives: new construction, chip seal, ACFC, 1 in. overlay + ACFC, 3 in. overlay + ACFC, and 6 in. overlay + ACFC. The ACFC was considered without rubber coat and heat scarifier. Information regarding benefits of a rubber coat and a heat scarifier was asked separately which is described later in this section. Twelve different combinations of region, traffic, and deflection were selected for each maintenance alternative (see Figure A-1). For each combination, the assessor (the pavement engineer) was asked to sketch the curve of how the roughness index of a pavement with the given independent variables and a given initial condition would vary with time. The engineer was also asked to specify the limiting RI value and the time in years when the pavement would reach the limiting value. Because of the uncertainties in material properties, traffic, and environmental conditions, exact prediction of how a pavement would perform is generally not possible. This uncertainty in pavement performance must be recognized in assessing subjective information. In view of the uncertainty, the assessors were asked to given their pessimistic, optimistic, and most expected estimates of pavement life. With the assumption of normal distribution, this range corresponds to (mean $\pm$ 3 standard deviations). Since the assessors were quite familiar with the concepts of mean m and standard deviation σ in a normal distribution, they were able to specify the range ($m \pm 3\sigma$) in accordance with their perception of the uncertainties involved. With regard to skid number, combinations of traffic, region, and aggregate type were considered. Three types of aggregate were included: aggregate 1, basalt or cinders; aggregate 2, gravel; and aggregate 3, limestone. A typical form for specifying performance curves is shown in Figure A-2.

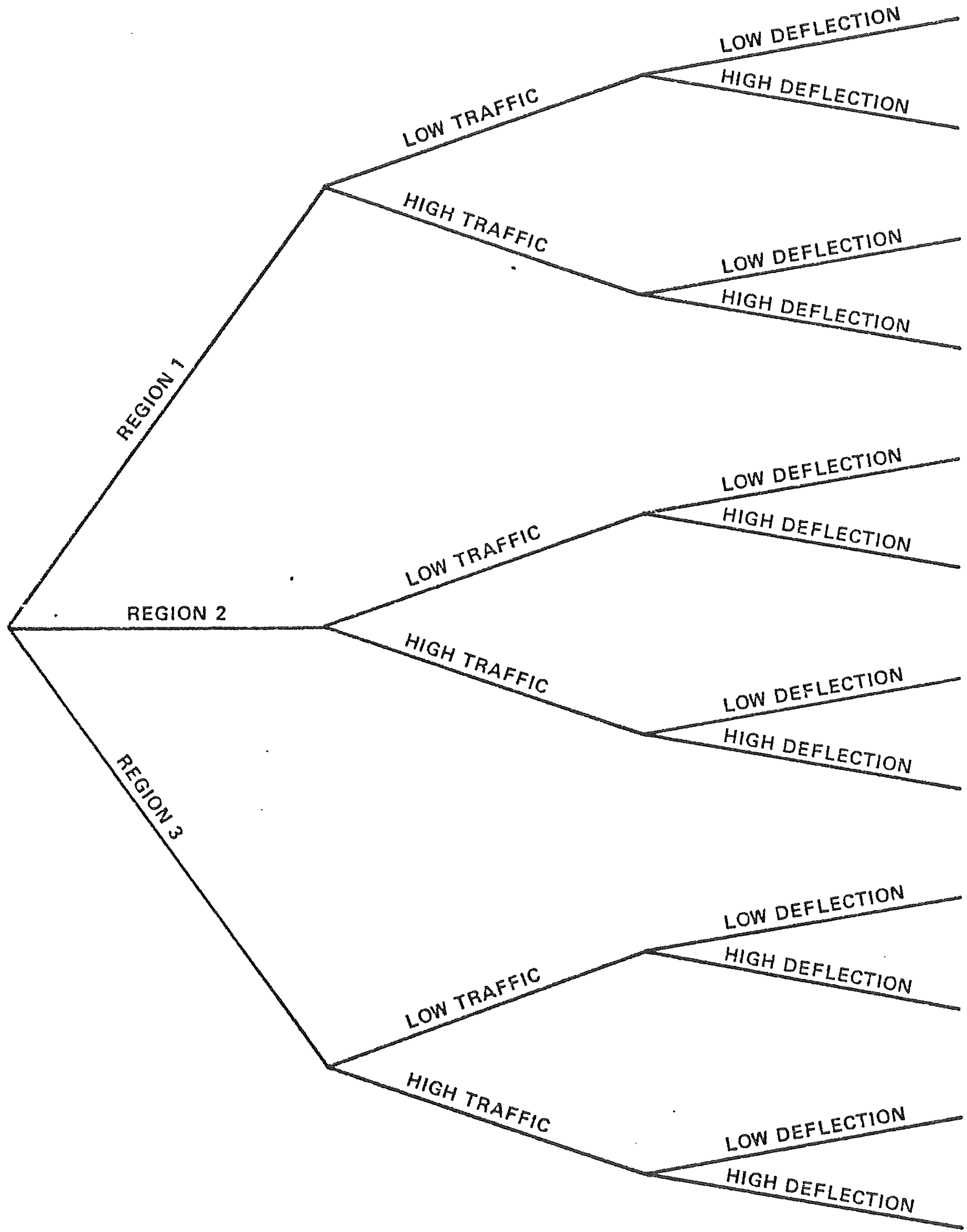


Figure A-1. PARAMETERS SPECIFIED IN ASSESSING PAVEMENT PERFORMANCE

AC PAVEMENTS (Routine Maintenance on Existing Pavements)

Region = Traffic = Current Deflection =

Age = Current RI =

On the following graph

- indicate which curve most appropriately describes the performance trend
- indicate the year when the limiting value would be reached

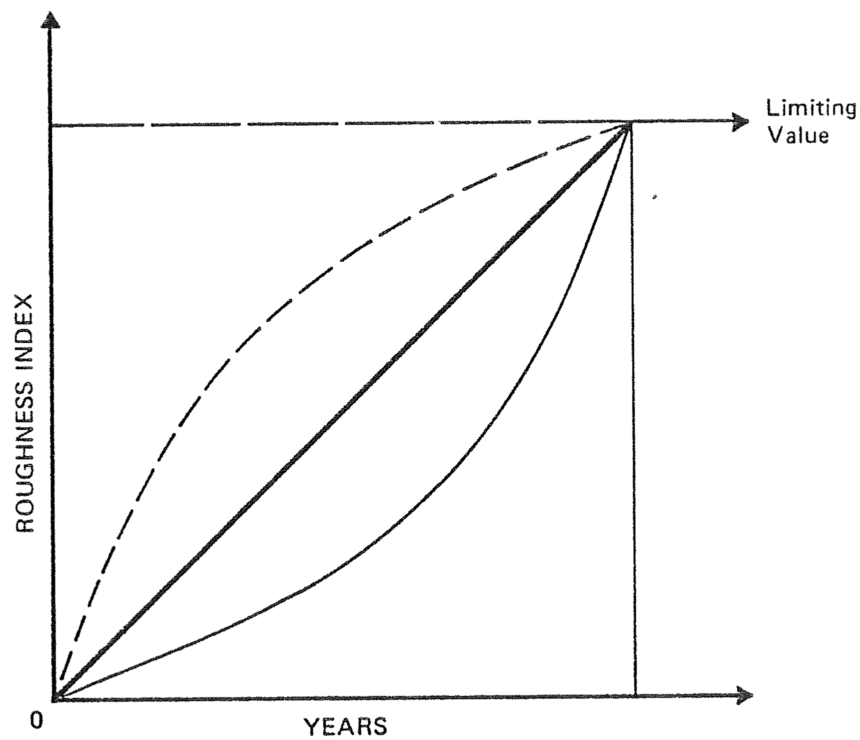


Figure A-2. A TYPICAL FORM FOR THE SPECIFICATION OF PERFORMANCE CURVE

In addition to the performance curves, information regarding pavement condition immediately following major maintenance was also obtained. For roughness index and skid number the information required is indicated in Figure A-3. For different major maintenance alternatives and for different prior conditions under each alternative, responses regarding posterior roughness index were obtained (see Figure A-4). Similarly, mean and standard deviation of skid numbers immediately following ACFC or seal coat with different aggregate types were also obtained from the assessors.

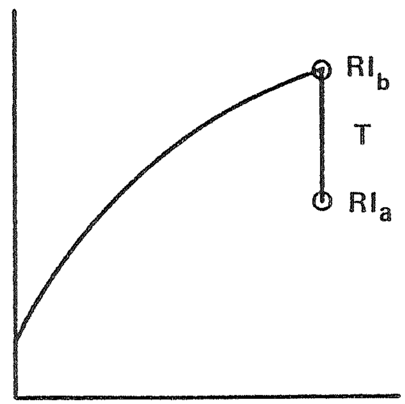
Use of all this information obtained from the Arizona DOT staff in generating subjective data points is described in the next section.

GENERATION OF SUBJECTIVE DATA THROUGH SIMULATION

In the previous step, performance curves were obtained for different combinations of appropriate independent variables. Next, six hypothetical pavements were selected with the given values of the independent variables. Performance of each pavement was determined from the assessed subjective information and performance data was then generated for that pavement. Because of the uncertainties indicated by the range of pavement life, all the six pavements with the same properties might not perform in an identical manner. A simple Monte Carlo simulation procedure was used to determine which performance path a given pavement would follow (see Figure A-5). A random number from a normal distribution with mean zero and standard deviation 1 was generated for each pavement. If this number was between -1 and -3, the pavement was assumed to have a life of $(m - 2\sigma)$; if the random number was between -1 and 1, the mean (expected) pavement life was assumed; and if the number was between 1 and 3, a pavement life of $(m + 2\sigma)$ was assumed.

After the appropriate performance curve was determined, the curve was drawn on graph paper showing the relationship between the dependent

(I) Roughness Index Immediately Following Major Maintenance



RI_b = roughness index prior to major maintenance

RI_a = roughness index immediately following major maintenance

T = thickness of given major maintenance

$RI_a = f(RI_b, T)$

Figure A-3. SUBJECTIVE INFORMATION ON PAVEMENT CONDITION IMMEDIATELY FOLLOWING MAJOR MAINTENANCE

(II) Skid Number Immediately Following ACFC or Seal Coat

SNA = average skid number immediately following ACFC or seal coat

SNSD = standard deviation of skid number immediately following ACFC or seal coat

(SNA, SNSD) = f (aggregate type)

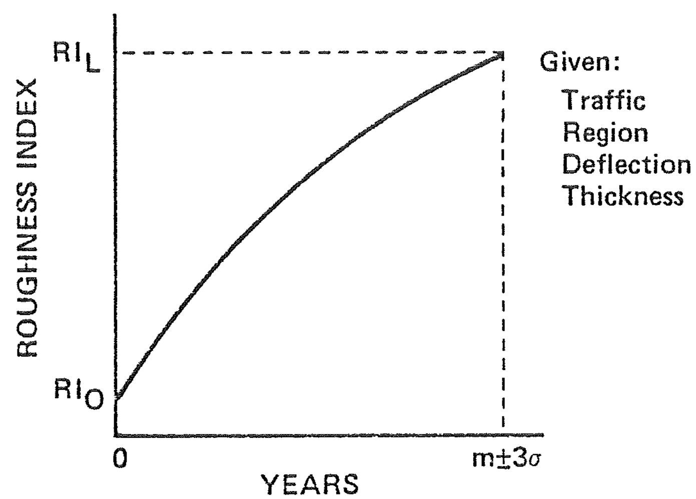
Figure A-3. SUBJECTIVE INFORMATION ON PAVEMENT CONDITION IMMEDIATELY FOLLOWING MAJOR MAINTENANCE (Continued)

AC PAVEMENTS (Major Maintenance on Existing Pavements)

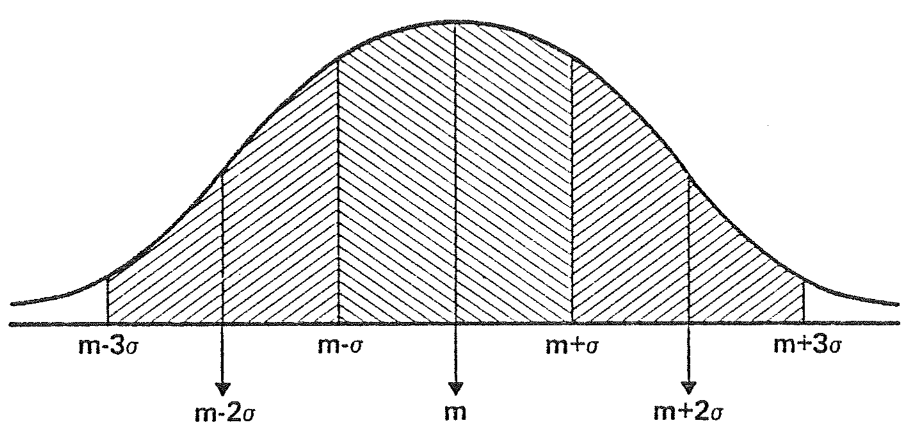
Indicate the effect of a given type of major maintenance on roughness index in the following table

Type of Major Maintenance	RI Prior to Major Maintenance	RI immediately after Major Maintenance
1. ACFC without rubber coat, without heat scarifier	0 – 10	
	10 – 20	
	20 – 30	
	30 – 40	
	40 – 50	
2. 1" overlay, plus ACFC without rubber coat, without heat scarifier	0 – 10	
	10 – 20	
	20 – 30	
	30 – 40	
	40 – 50	
3. 3" overlay, plus ACFC without rubber coat, without heat scarifier	0 – 10	
	10 – 20	
	20 – 30	
	30 – 40	
	40 – 50	
4. 6" overlay, plus ACFC without rubber coat, without heat scarifier	0 – 10	
	10 – 20	
	20 – 30	
	30 – 40	
	40 – 50	

Figure A-4. A TYPICAL FORM FOR SPECIFYING SUBJECTIVE INFORMATION REGARDING PAVEMENT CONDITION IMMEDIATELY AFTER MAJOR MAINTENANCE



RESPONSE FROM ARIZONA DOT STAFF



MONTE CARLO SIMULATION FOR HANDLING UNCERTAINTY

Figure A-5. USE OF SUBJECTIVE INFORMATION IN THE SIMULATION SCHEME variable (roughness index or skid number) and time in years. Points were then selected from this curve for the change in roughness index or skid number every two years (see Figure A-6). The change in the variable rather than the absolute value was selected as the dependent variable so as to reduce autocorrelations between successive values of the dependent variable. The selection of a unit time period of two years (instead of, say, one year) was predicated on the assumption that changes in roughness index or skid number (SN) in two years would be significant and show a reliable trend.

The above procedure was used for all the six hypothetical pavements for a given combination of independent variables. This was then repeated for every combination of independent variables for which performance curves were assessed. After all the subjective data points were generated, these were tabulated in a format suitable for multiple regression analysis. Discussion regarding results of regression analysis is given in the next section.

USE OF PERFORMANCE DATA IN MULTIPLE REGRESSION ANALYSES

Using the procedure outlined in the previous section, data points were generated for the following cases:

Dependent Variable	Independent Variables	Number of Data Points
Change in RI for new or in-service pavement	Region, deflection, traffic, age	283
Change in RI following major maintenance	Region, deflection, traffic, overlay thickness, age	1037
Change in SN for in-service pavement without ACFC	Region, age, traffic, aggregate type	352
Change in SN following ACFC or chip seal	Region, age, traffic, aggregate type	519

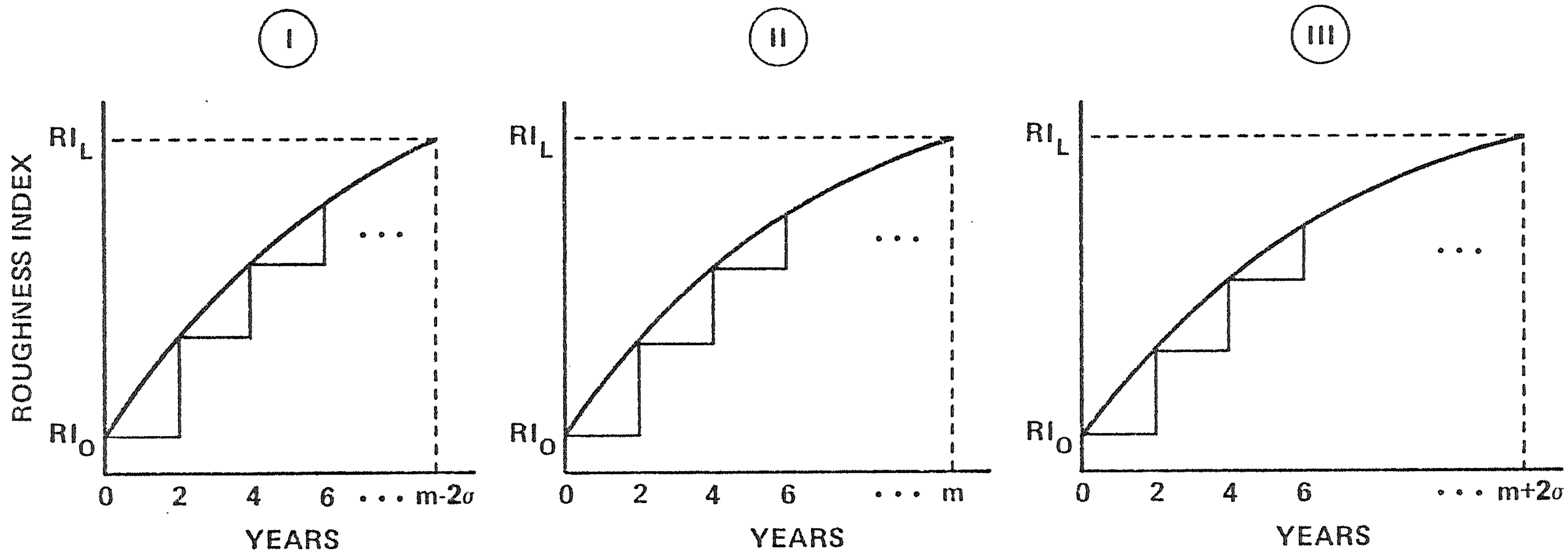


Figure A-6. GENERATION OF DATA ON CHANGE IN ROUGHNESS INDEX

It should be noted that only one equation was developed for change in SN following ACFC or chip seal. The reason for this was that the assessed performance curves for skid number following the two maintenance alternatives, namely ACFC and chip seal, were quite similar. With regard to traffic, average traffic at the middle year during any given time period of two years was used.

Different forms of regression equations were tried until sufficient predictive accuracy as indicated by multiple correlation coefficient and standard error was obtained. After a particular form was selected, outliers were examined and some of them were eliminated. The final regression equations developed for the four dependent variables shown earlier are as follows:

(1) change in RI (CRI) for new or in-service pavement

$$\ln(CRI) = 1.66 + 0.882 \ln(RGN) + 0.696 \ln(DEFL) + 0.19 \ln(TRAF) + 0.422 \ln(AGE)$$

$R^2 = 0.838$ Standard Error = 0.212

(2) change in RI following major maintenance

$$\ln(CRI) = 1.274 + \ln(CRH) + 0.874 \ln(RGN) + 0.328 \ln(DEFL) + 0.0718 \ln(TRAF) - 0.0375 \ln(THIK) + 0.4618 \ln(AGE)$$

$R^2 = 0.76$ Standard Error = 0.221

The significance of the variable CRH is explained later.

(3) Change in SN for in-service pavement without ACFC

$$\ln(CSN) = 1.972 + 0.1147 \ln(RGN) - 1.459 \ln(AGE) + 0.101 \ln(TRAF) + 0.9393 \ln(AGT)$$

$R^2 = 0.91$ Standard Error = 0.2198

(4) Change in SN following ACFC or chip seal

$$\ln(CSN) = 1.942 + 0.294 \ln(RGN) - 1.005 \ln(AGE) + 0.0594 \ln(TRAF) + 0.6949 \ln(AGT)$$

$R^2 = 0.788$ Standard Error = 0.304

where

RGN = environmental region
DEFL = deflection
TRAF = average annual traffic
AGE = age of the pavement in years
THIK = overlay thickness in inches
CRH = correction factor for rubber coat or heat scarifier

The variable CRH in the second equation above specifies a correction factor for taking into account the benefit of rubber coat or heat scarifier. The performance information was obtained for major maintenance alternatives with ACFC but without rubber coat or heat scarifier. The change in roughness index would be smaller if either rubber coat or heat scarifier was used. The factor CRH indicates how much smaller the change would be. For example, a CRH of 0.7 would imply that the change in RI is 0.7 times the change calculated assuming neither rubber coat nor heat scarifier. To specify CRH for a maintenance alternative with either rubber coat or heat scarifier, one could consider the increase in the pavement life of such a treatment. Let us say that the increase in pavement life for a particular alternative is x%. Then CRH for this alternative may be specified as (100/(100 + x)).

In addition to the regression equations predicting change in RI or SN following a particular maintenance alternative, it was also necessary to predict pavement condition (RI or SN) immediately following a given major maintenance alternative. The type of information which was obtained is shown in Figure A-3. A regression equation, with roughness index (RI_a) immediately after given major maintenance as a dependent variable and with roughness index (RI_b) prior to major maintenance and overlay thickness as independent variables, was developed. This equation is shown below.

$$\ln(RI_a) = 1.628 + 0.309 \ln(RI_b) - 0.237 \ln(THIK)$$

$R^2 = 0.921$ Standard Error = 0.099

As regards skid number immediately following ACFC or seal coat, two parameters, namely mean SNA and standard deviation SNSD can be specified for the aggregate type to be used in ACFC or seal coat.

DECISION ANALYSIS APPROACH TO THE DEVELOPMENT OF A PAVEMENT MANAGEMENT SYSTEM

The primary objective of a Pavement Management System (PMS) is to provide decision making information regarding the best maintenance strategy for a given pavement section. The best maintenance strategy would be determined, with regard to its consequences (or impacts), in terms of the following attributes:

- Skid number (SN)
- Present serviceability index (PSI) (or roughness index (RI))
- Traffic delay (TD) due to maintenance
- Equivalent annual dollar cost (EAC)

The decision analysis approach for selecting the best maintenance strategy can be divided into the following steps:

(a) Generation of feasible maintenance strategies

(b) Determination of consequences of each strategy

(c) Calculation of relative desirability or attractiveness of each strategy

(d) Determination of preferential ranking of the feasible maintenance strategies

These steps are described in the following sections. Throughout the discussion the basic concepts are illustrated in the context of a simple example. The discussion is practical and informal; for a more rigorous and formal description of the decision analysis, the book by Keeney and Raiffa may be consulted.*

*Keeney, R.L. and H. Raiffa, "Decision Analysis with Multiple Conflicting Objectives," John Wiley and Sons, New York, 1976.

Generation of Feasible Maintenance Strategies

A maintenance strategy in the context of a PMS is defined as the specification of timing and type of major maintenance to be performed during a designated analysis period. A maintenance strategy is considered to be feasible if it maintains pavement condition above the minimum acceptable standards as specified by the engineer. Because of the uncertainties in the prediction of pavement condition, one can guarantee maintaining the minimum standards only with a specified reliability; for example, a reliability of 90% implies that the chance that the pavement condition would be worse than the minimum required is at the most 1 in 10. In generating feasible strategies, both corrective and preventive maintenance modes must be considered. Corrective maintenance implies maintenance at or after the time the pavement condition becomes unacceptable; preventive maintenance, on the other hand, implies maintenance prior to reaching unacceptable condition.

The generation of feasible maintenance strategies can best be explained by means of a simple example where, for the sake of simplicity, only two attributes — present serviceability index (PSI) and cost — are considered. Let us suppose that we would like to formulate the best maintenance strategy for an in-service pavement with a present PSI of 3.0. Based on past experience and field measurements, we can predict the future PSI of this pavement. Because of the uncertainties in our ability to predict the PSI, we would obtain a distribution on the predicted PSI rather than a single value. Figure B-1 shows these distributions at different times during the analysis period. It must be pointed out that the prediction of PSI at any time period i is dependent on the on the PSI at time period (i-1) which is not known with certainty. The probability distribution of PSI at i^{th} time period is, therefore, obtained by combining the probability of a particular PSI value at period (i-1) and the conditional probability of the PSI at i given the PSI at (i-1) and integrating over all possible PSI values at (i-1).

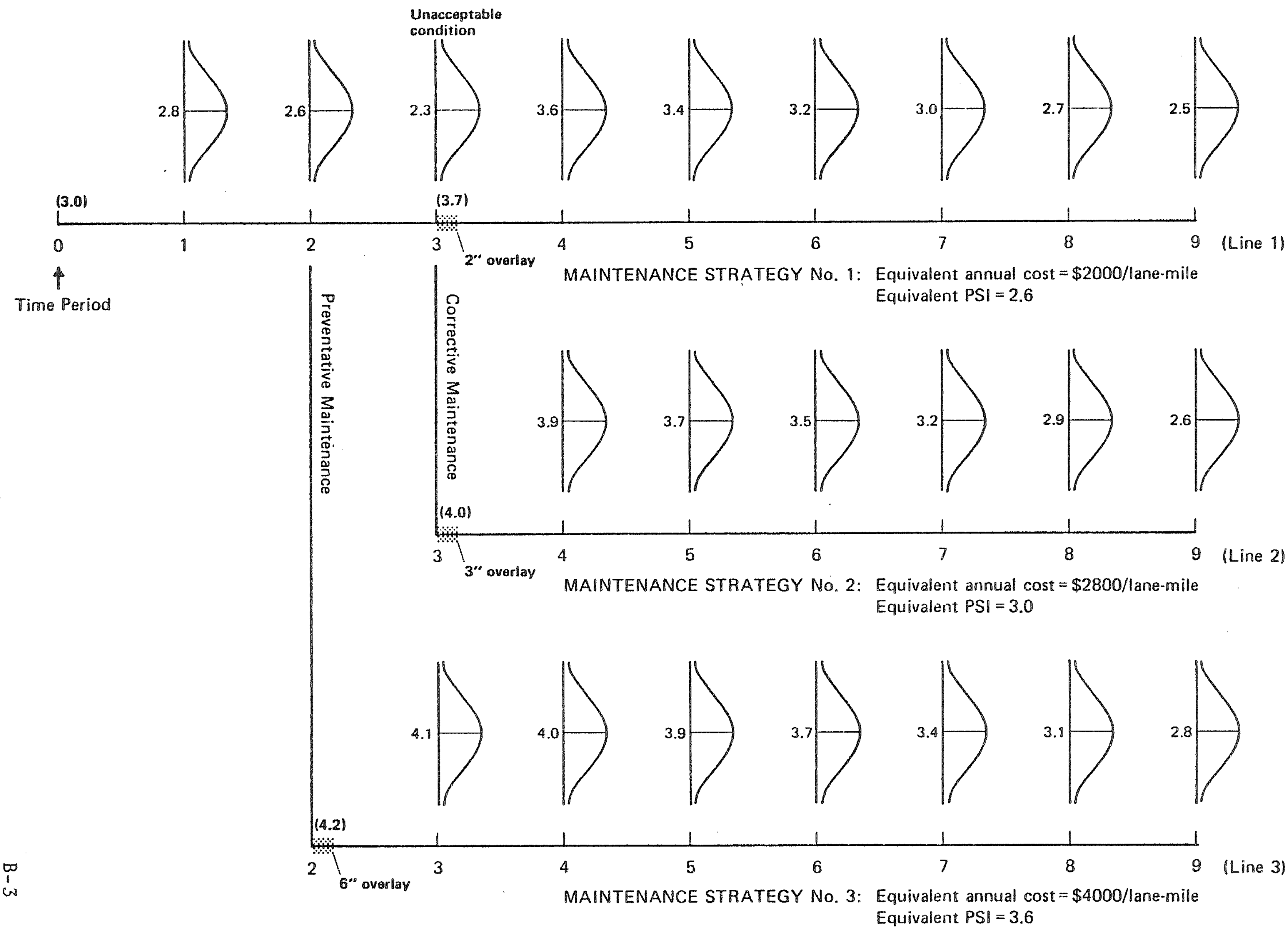


Figure B-1. CONSIDERATION OF UNCERTAINTIES IN PAVEMENT PERFORMANCE

In the implementation of this approach, various PSI values were generated using a Monte Carlo simulation procedure. This procedure is described in Appendix A.

The engineer may specify that the expected PSI of the section should remain above a limiting value of, say, 2.5 (this would correspond to a reliability of 50%). Following the performance history of the original pavement shown in Figure B-1 (line 1), it is seen that the expected PSI is 2.3 at the end of the third time period. Since this is an unacceptable condition, a corrective action must be taken at this time. Supppose a 2-in. overlay is applied to the pavement which brings the PSI to 3.2. Following the overlay the expected PSI remains above 2.5 through period 9 (Figure B-1, line 1); hence, no other action except routine maintenance is necessary for the remainder of the analysis period.

Instead of applying a 2-in. overlay, one could also consider other maintenance altermatives. For purposes of discussion let us suppose that the engineer schedules a 3-in. overlay at the end of the third time period (Figure B-1, line 2). The expected PSI is maintained above 2.5 following the overlay; hence, no further action is necessary.

Both of the strategies considered so far adopt corrective maintenance, that is, maintenance after unacceptable conditon is reached. However, the option of preventive maintenance, that is, maintenance prior to reaching unacceptable condition, must also be considered. Again for simplicity we will consider only one preventive action, namely a 6-in. overlay at the end of the second time period (Figure B-1, line 3). No further action is necessary following this overlay, since expected PSI remains above 2.5 during the remainder of the analysis period.

Thus, for the illustrative example, three feasible maintenance strategies are generated as shown in Figure B-1. Of course, by considering other maintenance alternatives such as ACFC with or without rubber coat and with or without heat scarifier along with different overlay thicknesses, many additional feasible strategies can be generated. The objective of the example was only to illustrate the logic used in generating feasible maintenance strategies.

Determination of Consequences of Each Feasible Strategy

The process of generating feasible maintenance strategies also provides the predictions of skid number and PSI at each time period during the designated analysis period. Using certain time delay models (for example, SAMP6 models), traffic delay due to maintenance activities to be scheduled under each strategy can be calculated. Also the equivalent annual cost of each strategy can be calculated using the cost models described in the main body of the report. Thus, the consequences (with their associated uncertainties) of each feasible strategy in terms of the four attributes — skid number, PSI, traffic delay and cost — can be determined. Because of the conflict between the performance attributes and the cost attribute, one particular strategy would not be the best with respect to all the attributes. Generally speaking, better pavement performance can be achieved through additional expenditure. To determine the best strategy, therefore, the decision maker's perception of incremental user benefits of better performance must be balanced against the incremental cost of achieving better performance. A formal preference structure of the decision maker is established for this purpose. This part of the analysis is discussed in the next section.

Calculation of Relative Desirability or Attractiveness of Alternative Maintenance Strategies

Through the previous steps, the alternative maintenance strategies are selected and consequences of each strategy in terms of probability distributions of the attributes over time are determined. The process of evaluating the alternative strategies in terms of overall desirability involves the following steps:

- o Establishing scalar utility functions incorporating the decision maker's attitudes towards risk
- o Incorporating time effects
- o Assessing tradeoffs between conflicting attributes
- o Calculating expected utility of each alternative strategy.

These steps are described below. The example shown in Figure B-1 is used for illustrating the basic concepts.

Establishing scalar utility functions. A scalar utility function is a mathematical expression for the decision maker's preferences for different levels of an attribute. The preferences are assessed under specified conditions of uncertainty. To illustrate the procedure involved in assessing a scalar utility function, let us consider the situation where there is a probability p that the PSI at a particular time period is x_1 and a probability (1-p) that the PSI is x_2. This is termed as a lottery situation because of the uncertainty involved. For example, on a particular section of road the following predictions are made based on uncertainties associated with past experience:

(a) there is a 50% chance that the PSI will be 3.5 at the end of ten years

(b) there is a 50% chance that the PSI will be 2.5 at the end of ten years.

The two possible outcomes represent what will be referred to as a lottery situation. We would like to replace the lottery by a single number to facilitate analysis; yet, at the same time, we do not want to change the relative preference (utility, worth) of the strategy involving the lottery. This would be possible only if the single number replacing a lottery is just as desirable as the lottery. Thus, in comparision with the lottery situation, it is necessary to determine that guaranteed level of PSI at which the decison maker would either be satisfied or would be just willing to try the lottery; that is, he would be indifferent whether to accept the guaranteed, sure outcome or to play the lottery. This guaranteed or sure outcome is referred to in decison theory as the "certainty equivalent (CE)" of the specified lottery.

The implication of the certainty equivalent is that if a sure outcome slightly less desirable than the CE is offered, the decision maker would rather take his or her chances on the associated lottery; on the other hand, if the sure outcome is slightly more desirable than the CE, he or she would accept the sure outcome in lieu of the lottery. To illustrate this point, consider a lottery with a 50% chance of getting a PSI of 3.5 and a 50% chance of getting a PSI of 2.5. If the sure outcome of 3.3 is offered, which would you choose – the lottery or the sure outcome? Pictorially this situation is represented as follows:

<u>Lottery</u>		<u>Sure Outcome</u>
50%	PSI = 3.5	
		PSI = 3.3
50%	PSI = 2.5	

Most engineers would choose the sure outcome of 3.3 in the above situation. If the sure outcome is 2.6 instead of 3.3, one might prefer the lottery with the reasoning that 2.6 is not much better than 2.5, the worst outcome in the lottery; hence, he might as well take his chances at getting a PSI of 3.5 by playing the lottery. As we can see, the decision maker's certainty equivalent for the lottery lies in between 3.3 and 2.6. By discussing various intermediate levels with the decision maker, his certainty equivalent can be assessed. Let us label this CE_1. Thus, the above procedure can be represented as follows:

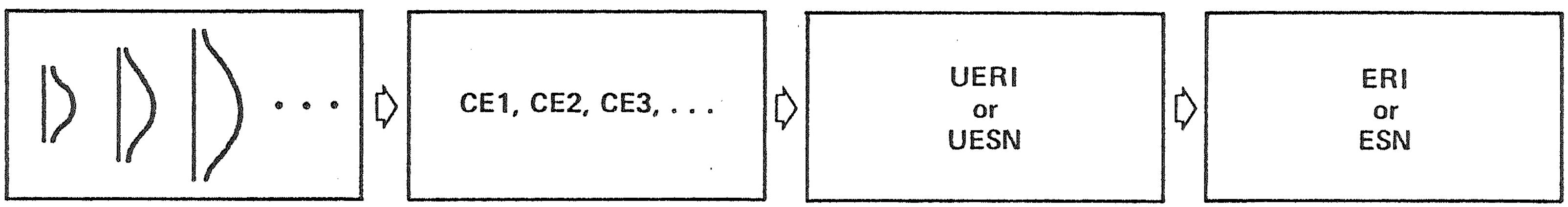
<u>Lottery</u>			<u>Sure Outcome</u>
50%	PSI = 3.5		~~3.3~~
		$\sim$	~~3.1~~
		(indifferent to)	$\boxed{2.9}$
			~~2.7~~
50%	PSI = 2.5		~~2.6~~

The crossed out numbers indicate those sure outcomes which were considered but were ruled out as not being the certainty equivalent of the lottery. Finally, at 2.9 for a sure outcome, indifference was found implying $CE_1 = 2.9$. This response is boxed in the above diagram.

By assessing a few representative certainty equivalents it is generally possible to establish a preference function (also referred to as a utility function) over the range of interest of the attribute under consideration. This preference function (utility function) can then be used to compute certainty equivalents of all the uncertain situations which may have to be studied in determining the best maintenance strategy.

Incorporating time effects. In evaluating alternative maintenance strategies, consquences of each one in terms of the selected attributes must be compared over an analysis period of, say, 15 to 20 years. Because of uncertainties, the consequences are specified by probability distributions at each time period. The scheme for converting a string of probability distributions into an equivalent number is shown in Figure B-2. First, each probability distribution is replaced by its certainty equivalent calculated by using the scalar utility function. Next, the average of the utilities of all the certainty equivalents is calculated and finally, the equivalent level of the attribute corresponding to the average utility is obtained. This procedure assumes additive preferences over time. The implications of this assumption are that the scalar utility function remains unchanged over time and that a given level of an attribute at any time during the analysis period is equally desirable.

Continuing with the illustrative example shown in Figure B-1, let us suppose that the assumption of additive preference over time is reasonable. Using the above procedure, the attributes of PSI and annual cost in dollars per lane for the three alternative maintenance strategies can be summarized as shown in Table B-1.



probability distributions of pavement condition over time for a given maintenance strategy.

certainty equivalent of each probability distribution using utility function.

average utility over roughness index or skid number for the given strategy.

equivalent roughness index or skid number of the given strategy over the entire analysis period.

Figure B-2. CONVERSION OF A STRING OF PROBABILITY DISTRIBUTIONS INTO AN EQUIVALENT NUMBER

Table B-1.

Maint. Strategy #	Equivalent PSI	Equivalent Annual Cost
1	2.6	$2,000
2	3.0	$2,800
3	3.6	$4,000

Assessing tradeoffs between conflicting attributes. If only one attribute was of concern, the decision of best strategy would be relatively simple. For example, from the consideration of cost alone, maintenance strategy #1 in the above table is best while from the consideration of PSI alone, maintenance strategy #3 is best. When both cost and PSI are to be considered, the best strategy is intuitively not so obvious. It appears that maintenance strategy #2 requires an incremental cost of $800 per lane-mile per year to maintain the PSI at 3.0 instead of at 2.6. Similarly maintenance strategy #3 requires an additional cost of $2000 per lane-mile per year to maintain the PSI at 3.6 instead of at 2.6. To decide the best strategy, one must determine whether the specified increase in the PSI is worth the corresponding increase in the cost. Issues of this type must be resolved on the basis of the decision maker's perception of incremental benefits of higher PSI in relation to the incremental cost of maintaining the higher PSI.

Thus, for a decision making problem involving multiple and often conflicting attributes, it becomes necessary to establish how much the decision maker is willing to sacrifice on one attribute in order to achieve on some other attribute. These are termed the preference tradeoffs between the conflicting attributes. To illustrate the procedure for assessing tradeoffs, consider maintenance strategies #1 and #3 for the illustrative example shown in Figure 1 and summarized in Table B-1. Which of the two strategies would you prefer? This would depend upon whether one is willing to spend an additional amount of $2000 per lane-mile per year in order to maintain the PSI at 3.6 instead of at 2.6.

Let us suppose that strategy #3 is preferred; that is, benefits of higher PSI are perceived to be greater than the corresponding increase in cost. Suppose that the PSI of strategy #3 is maintained at 2.8 instead of at 3.6. Now strategy #1 might very well be preferred with the argument that increasing PSI from 2.6 to 2.8 is not worth the additional cost of $2000 per lane-mile per year. Obviously between the PSI of 3.6 and 2.8 there is a level of PSI at which the decision maker might feel indifferent between the two strategies, that is, at that level both the strategies might appear to be equally attractive. The objective of the tradeoff analysis would be to establish the indifference point between various levels of confliciting attributes. It is not necessary to establish tradeoffs between all possible combinations of the concerned attributes. By assessing a few typical tradeoffs, it is generally possible to establish an overall utility function which would be applicable to all practical situations one may have to face in making decisions.

Calculating expected utility of each alternative strategy. The individual utility functions assessed for each of the attributes represent the preferences for various levels of the attribute. The multiattribute utility function can be expressed as a simple function of the individual attribute utility functions under certain conditions. These conditons are referred to as preferential independence and utility independence.

A pair of attributes (X_i, X_j) is said to be preferentially independent of other attributes if preferences among (X_i, X_j) pairs do not depend on the level at which the others are fixed, given that the others are held fixed at some level. Preferential independence implies that the tradeoffs between attributes X_i and X_j do not depend on the values of the other attributes.

The attribute X_i is said to be utility independent of the other attributes if preferences among lotteries over X_i (that is, lotteries with uncertainty about the level of X_i only), given that the other attributes are held fixed, do not depend on the level at which these other attributes are fixed.

If the number of attributes is three or more, and if for some X_i, (X_i, X_j) is preferentially independent of the other attributes for all $j \neq i$, and X_i is utility independent of all the other attributes, then either

$$u(\underline{x}) = \sum_{i=1}^{n} k_i u_i(x_i) \qquad \text{if } \Sigma\, k_i = 1 \qquad \text{(B-1)}$$

or

$$u(\underline{x}) = (\{\prod_{i=1}^{n} [1 + k k_i u_i(x_i)]\} - 1)/k \qquad \text{if } \Sigma\, k_i \neq 1 \qquad \text{(B-2)}$$

where:

u = multiattribute utility function scaled between 0 and 1
x_i = level of i^{th} attribute
$u_i(x_i)$ = individual utility function for X_i scaled between 0 and 1
k = constant with value -1 or greater
k_i = scaling constants with values between 0 and 1.

The k_i are scaling constants which express the tradeoffs that exist among the attributes. The constant k can be determined from the k_i's. Thus, the multiattribute utility function can be completely defined when the individual attribute utility functions and the scaling constants, k_i, are known.

The expected utility of each alternative maintenance strategy can be calculated from the multiattribute utility function and the equivalent levels of all the attributes for the strategy. Let $\hat{x}_i^j$ denote the equivalent level of i^{th} attribute for the j^{th} strategy. The expected utility $E(u_j)$ of the j^{th} strategy assuming a multiplicative form for the overall utility function is given by:

$$E(u_j) = \frac{1}{k}\left\{\prod_i [1 + kk_i u_i(\hat{x}_i^j)] \quad - 1\right\} \qquad \text{(B-3)}$$

Determination of Preferential Ranking of the Feasible Maintenance Strategy

In decision problems involving uncertainty, the expected utility is the appropriate criterion for determining preferential ranking of alternative actions. This property follows from certain behavioral assumptions postulated by Von Neumann and Morgenstern.* The alternative with the highest expected utility is the most preferred.

The direct interpretation of the differences in the expected utility of alternative strategies to identify the magnitude of differences in the relative desirability of the strategies is difficult. One useful exercise in this respect is to calculate the 'net benefit' in dollars of the best strategy over all other strategies. The net benefit of the best strategy over another strategy can be defined as the increment in the cost of the best strategy which would make its expected utility equal to that of the other strategy. The difference in the expected utilities of the two strategies can be interpreted as being equivalent to the net benefit in dollars.

Implementation of the Decision Analysis Approach for Developing a Pavement Management System

Development of the prediction models for determining consequences of a given maintenance strategy is described in the main report and in Appendix A. In this section the assessment of the multiattribute utility function is described.

A number of people were assessed for their preferences regarding individual attributes and tradeoffs between attributes. The procedure

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*Von Neumann, J. and O. Morgenstern, "Theory of Games and Economic Behavior," 2nd Edition, Princeton University Press, 1947.

used was one-on-one interviews. The assumptions of preferential and utility independence, and additive preferences over time were checked with each assessor and were found to be reasonable. After studying the results of all the assessments, two distinct preference structures were identified. Each preference structure was quantified by averaging over the responses of the persons who were close to that preference structure. Preference structure 1 was identified as that for District 1 and preference structure 2 was identified as that for District 7. The multiplicative form of the utility function was applicable for both the Districts. The two functions are given below.

Scalar Utility Functions

Attribute	Worst Level	Best Level	Scalar Utility Function
X_i=skid number	25	100	$u_1(x_1) = 1.081\{1-\exp[-0.0345(x_1-25)]\}$ for both Districts
X_2=PSI	2	4	$u_2(x_2) = (x_2-2)/2$ for District 1 $u_2(x_2) = 1.385\{1-\exp[-0.6396(x_2-2)]\}$ for District 2
X_3=traffic delay in minutes	30	0	$u_3(x_3) = (30-x_3)/30$ for both Districts
X_4=equivalent annual cost in $ per lane-mile	10000	300	$u_4(x_4) = (10000-x_4)/9700$ for both Districts

Scaling Constants

District	K_1	K_2	K_3	K_4
1	0.70	0.42	0.292	0.378
7	0.685	0.216	0.036	0.70

The significant differences between the two utility functions are with respect to the tradeoffs between attributes and the resulting scaling constants. The order of decreasing relative importance of the four attributes for the District 1 function is: skid number, PSI, cost, and traffic delay. The decision maker with this preference structure would be willing to pay $9700 per year per lane-mile in order to improve the skid number from 25 to 45 and the same amount of money to improve the PSI from 2 to 3.8.

The utility function for District 7 indicates that the order of decreasing rleative importance of the attributes was: cost, skid number, PSI, and traffic delay. In this case the decision maker would be willing to pay $9500 per year per lane-mile only if the skid number improved from 25 to 100 and he would pay up to $3000 per year per lane-mile to improve the PSI from 2 to 4.